Renewable and Sustainable Energy Reviews 16 (2012) 5331–5348

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review on solar cold production through absorption technology

H.Z. Hassan [a,b,c,*], A.A. Mohamad [a,b]

[a] Mechanical and Manufacturing Engineering, Schulich School of Engineering, University of Calgary, 2500 University Drive, NW, Calgary, Alberta, Canada T2N 1N4
[b] College of Engineering, Alfaisal University, Riyadh, Saudi Arabia
[c] Mechanical Power Engineering Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt

ARTICLE INFO

Article history:
Received 20 October 2011
Received in revised form
27 April 2012
Accepted 28 April 2012
Available online 5 July 2012

Keywords:
Solar energy
Refrigeration
Heat pumps
Energy
Sorption
Absorption

ABSTRACT

Recently, the traditional energy types have failed to satisfy the human needs because of their limited quantity as well as their negative environmental impacts. Conventional cold producing machines that are based on vapor compression principle are primary electricity consumers and their working fluids are being banned by international legislation. From this perspective, solar powered cooling systems as a green cold production technology are the best alternative. Absorption refrigeration is a mature technology that has proved its applicability with the possibility to be driven by low grade solar and waste heat. In this study, we present a comprehensive literature review on absorption based refrigeration and air conditioning systems that are powered by solar energy. Various systems along with their thermodynamic operating principle are presented. Moreover, the previous experimental and numerical simulation studies for these systems are discussed.

Contents

1. Introduction

Energy is an essential need for all human beings in the world, like water, food and shelter. The energy demand is basically affected by three major factors namely population, economy,

* Corresponding author at: Mechanical and Manufacturing Engineering, Schulich School of Engineering, University of Calgary, 2500 University Drive, NW, Calgary, Alberta, Canada T2N 1N4. Tel./fax: +1 403 7192677.
E-mail addresses: hzhahmed@ucalgary.ca, hassan_zohair@zu.edu.eg (H.Z. Hassan), mohamad@ucalgary.ca (A.A. Mohamad).

1364-0321/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.04.049

and the per capita energy consumption. Increasing rates of these factors is the major force that will be continued to cause increase in energy demand during the coming decades. Moreover, there is enough scientific evidence of growing environmental problems due to combination of different factors, such as increased population, energy consumption and industrial activities in the world [1]. Along with the increasing trend in the worldwide economic growth, much more of the world's energy is being consumed to drive the conventional refrigerating and air conditioning appliances in both industry and buildings to meet the cooling demands. These traditional vapor compression machines are dominating electricity consumers and their operation and propagation cause high electricity peak loads during the summer, especially in those countries with tropical climate. Approximately 10–20% of all the electricity produced in the whole world is consumed by various kinds of the refrigeration and air-conditioning machines, as estimated by the International Institute of Refrigeration [2]. The energy consumption for air conditioning systems has recently been estimated to be 45% of the whole households and commercial buildings [3]. The data and results discussed by Dunn et al. [4] provided analysis of the overall energy consumption and associated carbon emissions of 27 UK air conditioned office buildings. In their study, it is found that the proportion of energy consumed by the cooling only systems ranged from 3% to 43% of the whole building energy consumption and 21% on average. In addition, the proportion of energy used by reverse cycle air conditioning systems was 39% on average and ranged from 17% to 67% of the whole buildings energy consumption. Moreover, the conventional vapor compression systems use non-natural working fluids and refrigerants like the chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC) or hydrofluorocarbon (HFC). These refrigerants have high global warming as well as ozone layer depletion potentials. Moreover, they contribute significantly in an opposite way to the international regulations. It is known that the use of these systems contradicts with the Kyoto protocol on global warming (1998), the Vienna Convention for Protection of the Ozone Layer (1985), and Montreal Protocol on Substances Depleting the Ozone Layer (1987). Moreover, the European Commission Regulation 2037/2000, which has been implemented on 1 October 2000, treats the whole spectrum of control and phase-out schedule of all the ozone depleting substances. It is indicated that till 2015 all HCFCs will be banned for servicing and maintaining existing systems [5].

In addressing these issues, providing cooling by utilizing a clean and renewable energy such as solar energy is the key solution to decrease electricity requirements for cooling, peak electrical demand and energy costs without lowering the desired level of comfort conditions. For example, the Mediterranean countries may save 40–50% of their energy used for air conditioning by implementing solar driven air conditioning systems [6,7]. Even if 50% of present market of small air conditioning (AC) systems can be replaced by solar powered systems, a considerable worth of electrical energy can be saved and a good amount of carbon credit can also be earned [3]. The development of solar refrigeration technologies became the worldwide focal point for concern because the peaks of requirements in cold coincide most of the time with the availability of the solar radiation. Solar refrigeration has the potential to improve the life quality for people who live in remote areas or areas with insufficient electricity. Moreover, the solar cooling technology can reduce the environmental impact raised by conventional air-conditioning systems. That is because the refrigerants used in these systems are environmentally benign, natural refrigerants and are free from CFC. Therefore, these systems have zero ozone depleting as well as a zero global warming potentials.

2. Solar absorption cooling systems

Solar refrigeration is a technology that has a great variety of methods of producing low temperatures; however, very few have demonstrated a technical and economical viability [8]. During the recent decades, many research activities have aimed at the development of cold production technologies that are powered by the solar energy. Many systems and technologies have been developed and introduced in the literature and others are currently in progress. Solar absorption cooling, having the most published papers, has been studied more extensively than other systems. Research work has been carried out all over the world [9]. Balaras et al. [6] described the main results of the EU project SACE (Solar Air Conditioning in Europe), aimed to assess the state-of-the-art, future needs and overall prospects of solar cooling in Europe. In this study, it was counted that about 59% of the solar cooling systems in Europe were based on the absorption cooling technology.

Absorption is the phenomenon in which a substance in one state interpenetrates and incorporates into another of a different state. The two phases present a strong affinity to form a solution or a mixture. This process can be reversed and the absorbed phase can be released from the absorbent by applying heat to the mixture. The first absorption cooling machine which used water as the absorbent and ammonia as refrigerant was patented in France in 1859 by the French scientist Ferdinand Carré. The solar absorption cooling system uses two working fluids, the refrigerant and the sorbent, in a closed or open mode cycle. Absorption machines are thermally activated, and for this reason, high input shaft power is not required [10]. Its working principle is the same as the vapor compression machine except that the mechanical compressor is replaced by a thermal compressor.

The main advantage of the solar absorption cooling technology is that their coefficient of performance is higher than that of other thermally operated cycles. Moreover, the freedom from noise and vibrations, long lasting, cheap maintenance, and most importantly the possibility of using any type of heat source, including solar radiation and geothermal or waste heat, to energize the system and provide reliable cooling. The applications of these cooling systems are wide and include freezing, cooling, and air-conditioning. However, these systems are heavy in weight and have a relatively high initial cost. Moreover, in order to cover cooling capacities in the range of 10–30 kW, the required solar collector surface area will be about 30–100 m^2 [11]. Absorption cooling systems typically require an open wet cooling tower to transfer the rejected heat to the ambient. Yet, water consumption, the need for water make-up and cleaning, formation of fog, and the risk of Legionella bacteria growth are hindering factors for the implementation of small solar cooling systems. This is a crucial aspect for the implementation of solar cooling systems, especially when small capacity installations are in question. However, a low temperature latent heat storage together with a dry air cooler is a promising alternative to a conventional wet cooling tower [11].

The most studied systems use absorption cycles with liquid/vapor balance, in particular ammonia/water systems for refrigeration and the lithium bromide/water systems for the cooling of air [8]. There are three types of cooling production devices: closed cycle continuous absorption cooling system, closed cycle intermittent absorption cooling system and open cycle absorption cooling system.

3. Absorption cooling working pairs

Up to now, the commonly used and mature refrigerant–absorbent working pairs in the absorption refrigeration systems

are the H_2O–LiBr, and NH_3–H_2O pairs. Since each pair differs from the other in terms of the physical and thermodynamic properties, the choice of the working pair has a great effect on the system performance and the technical concerns. The choice criteria depends on a number of important requirements. These include [12]:

- The refrigerant latent heat should be high, so the circulation rate of the refrigerant and absorbent can be minimized.
- The refrigerant/absorbent pair should not form a solid phase over the expected range of composition and temperature to which it will be subjected.
- The refrigerant should be much more volatile than the absorbent so the two can be separated easily without the need to a rectifier.
- The absorbent should have a strong affinity for the refrigerant under conditions in which absorption takes place. Strong affinity allows less absorbent to be circulated for the same refrigeration effect, reducing sensible heat losses, and allows a smaller liquid heat exchanger.
- Moderate operating pressure is required. High pressure requires heavy-walled equipment, and significant electrical power may be needed to pump fluids from the low-pressure side to the high pressure side. Low pressure requires large-volume equipment and special means of reducing pressure drop in the refrigerant vapor paths.
- High chemical stability is required to avoid undesirable formation of gases, solids, or corrosive substances.

For example, in the case of water/lithium bromide working pair, the temperature lift is restricted due to crystallization and a need for anti-crystallization is necessary. LiBr is a salt and has a crystalline structure in its solid state and there is a specific minimum solution temperature for any given LiBr salt concentration below which the salt begins to crystallize out of the solution. LiBr begins to crystallize in the solution either when the concentration ratio is increased or when the solution temperature is reduced beyond the crystallization limit. It is more prone to occur for the strong solution entering the absorber. The risk of crystallization results in interruption of machine operation and possible damage to the unit because it leads to the formation of slush in the piping network, which may result in complete flow blockage if the slush is solidified. To avoid this, the concentrated solution temperature needs to be raised significantly above its saturation point in order to dissolve salt crystals [13]. Furthermore, water as a refrigerant has a high freezing point. As a consequence, the external evaporator temperature is restricted to temperatures above the freezing point of at least 5 °C. Moreover, lithium bromide as absorber is not totally soluble in water because of crystallization. Due to the high specific volume of water vapor as refrigerant and the evaporator vacuum, the machines are not very compact and need to be very tight. That is besides, the relatively high costs due to using the LiBr. However, this pair has high COP, large specific latent heat of vaporization (about 2489 kJ/kg at 5 °C), low operation pressures, as well as it is environmental friendly. Moreover, lithium bromide solution is not volatile and the working pair is odorless and neither toxic nor flammable. The H_2O–LiBr pairs are more suitable for cold water generation in chillers and air-conditioning purposes and are the most appropriate for the solar applications [14]. The desorber temperatures needed for the LiBr–water pair are in the range between 75 and 120 °C. As a consequence, flat plate collectors, compound parabolic collectors and evacuated tube collectors that are easy to install and operate can be manipulated.

The disadvantages of the ammonia/water pairs are the volatility of water as an adsorbent during desorption, so a rectification column is necessary. Furthermore, the ammonia is toxic, has a very unpleasant odor, and corrosive for the copper and copper-based tubes. Due to the high refrigerant operating pressure (up to 25 bar) at typical ambient air condensation temperatures, the costs of the machines are high [15]. The ammonia–water pair is not suitable for use with solar collectors because of the high temperature needed in the generator (125–170 °C). This temperature can only be obtained with medium concentration ratio parabolic collectors, which have increased maintenance requirements due to the need for tracking the sun. From the other side, the ammonia/water pair has high affinity, high stability, and there is no vacuum required for evaporator temperatures above −30 °C (ammonia has a boiling point temperature of −33.3 °C at 1 bar). By using ammonia as a refrigerant, the evaporator temperature can go down even to −60 °C (ammonia has a low freezing point at −77.7 °C at 1 bar). Consequently, the temperature range of the machines is suitable for both air-conditioning and for industrial refrigeration and freezing applications [15]. Up to now, researchers are still seeking more advantageous working pairs with good thermal stability, no corrosion and no crystallization. The main research focus is to change the characteristics of the well-known pairs in order to overcome the problems mentioned as well as to come up with new working pairs, see Table 1.

Table 1
Absorption fluid pairs.

Refrigerant	Absorbent	Reference
Water (H_2O)	Lithium bromide (LiBr)	Nakahara et al. [16], Yeung et al. [17], Li and Sumathy [18], Praene et al. [19]
	Aqueous ternary hydroxide (40% sodium hydroxide NaOH, 36% potassium hydroxide KOH and 24% cesium hydroxide CsOH)	Romero et al. [20]
	Ionic liquid (1-ethyl-3-methylimidazolium dimethylphosphate [EMIM][DMP])	Zhang and Hu [21], Ren et al. [22]
	Ionic liquid (1-ethyl-3-methylimidazolium ethyl sulfate [EMISE])	Zuo et al. [23]
	Ethylene glycol ($C_2H_6O_2$)	Abdelmessih et al. [24]
	Monomethylamine	Romero et al. [25]
Ammonia (NH_3)	Water (H_2O)	Gutiérrez [26], Jakob et al. [27], Sierra et al. [28]
	Calcium chloride ($CaCl_2$)	Worsøe-Schmidt [29]
	Strontium chloride ($SrCl_2$)	Worsøe-Schmidt [29], Erhard and Hahne [30]
	Lithium nitrate ($LiNO_3$)	River and Rivera [31]
	Water–NaOH mixture	Steiu et al. [32]
	IMPEX material (80% $SrCl_2$ and 20% graphite)	Bansal et al. [33]
Trifluoroethanol (TFE)	Tetraethylenglycol dimethylether (TEGDME)	Medrano et al. [34], Boer et al. [35]
Methanol (MeOH)	TEGDME	Medrano et al. [34], Boer et al. [35]

4. The single-effect absorption cycle

The typical solar absorption cooling system consists of a solar collector or concentrator, a hot fluid storage tank, an auxiliary heater, condenser, evaporator, and the thermal compressor. The thermal compressor is composed of a regenerator, containing the absorber, the absorber, and the mixture circulating pump. The power consumption of the solution pump is relatively small compared to that consumed by the mechanical compressor. When the solar collector can provide the heating capacity more than needed, the excess heat is stored in the hot fluid storage tank. When the solar collector cannot collect enough heat, the auxiliary heater is turned on to make up the needed heating capacity. When the solar collector cannot provide heat any more, the hot water stored in the storage tank is used together with the auxiliary heater

The single effect system is the simplest type of these systems. The main system components are shown in the schematic diagram in Fig. 1. It represents the majority of absorption systems available on the market and works with the solar flat plate collector at low temperatures. The cycle operation is depicted in the *P*–*T*–*X* Dühring plot in Fig. 2. The operation of the system starts at the absorber where the refrigerant vapor coming from the refrigerator is absorbed and forms a rich mixture. Since the absorption process is exothermic, the latent heat of the vapor to liquid phase change is released to the ambient in order to keep the absorber at the evaporator low pressure. The circulating pump brings the rich solution from the absorber low pressure towards the generator, or the desorber, high-pressure zone. Heat from the solar collector is added at the generator in order to allow the separation of the refrigerant fluid from the absorbent fluid. The poor solution turns over in the absorber by passing by a pressure-relief valve. The solution heat exchanger (SHX) is used for internal heat recovery to preheat the solution leaving the absorber with the hot concentrated solution leaving the generator to improve system efficiency. The desorbed refrigerant vapor flows towards the traditional cycle of condenser, expansion valve and evaporator.

The majority of solar cooling systems available in the market are based on the single-effect LiBr/H_2O absorption chillers. Almost all of these systems are driven with hot water from an ordinary flat plate or evacuated tubular solar collector [36]. During the following subsections, we will be discussing the studies that are found in the literature regarding the solar single effect adsorption cooling systems. These researches take two ways: the first to be discussed is the experimentation and testing path, while the second discussed path is the theoretical and simulation methods.

4.1. Experimental and testing studies

In 1977, Nakahara et al. [16] worked in developing the technology to utilize solar energy for heating, cooling and hot water supply on the basis of various technology for energy conservation in buildings. For the first step of this project a solar heating and cooling system with flat plate collectors and absorption refrigeration machine was installed in a one-storey office room 80 m^2 house in 1974. The absorption chiller was a single-effect H_2O/LiBr of 7.03 kW nominal cooling capacity and is assisted by a 32.2 m^2 array of flat-plate solar collectors. The experimental results during the summer period showed that the cooling capacity and the solar COP were 6.5 kW and 0.14, respectively. A solar-powered solid-absorption refrigerating system with flat-plate solar collectors is introduced by Worsøe–Schmidt [29]. The experimental investigation showed an overall COP of 0.10, corresponding to an ice production of 6 kg/m^2 of collector area.

To study the feasibility of utilizing solar power for comfort cooling in Hong Kong, Yeung et al. [17] designed and constructed a solar-powered absorption air-conditioning system on the campus of the University of Hong Kong. The system consisted of a flat-plate

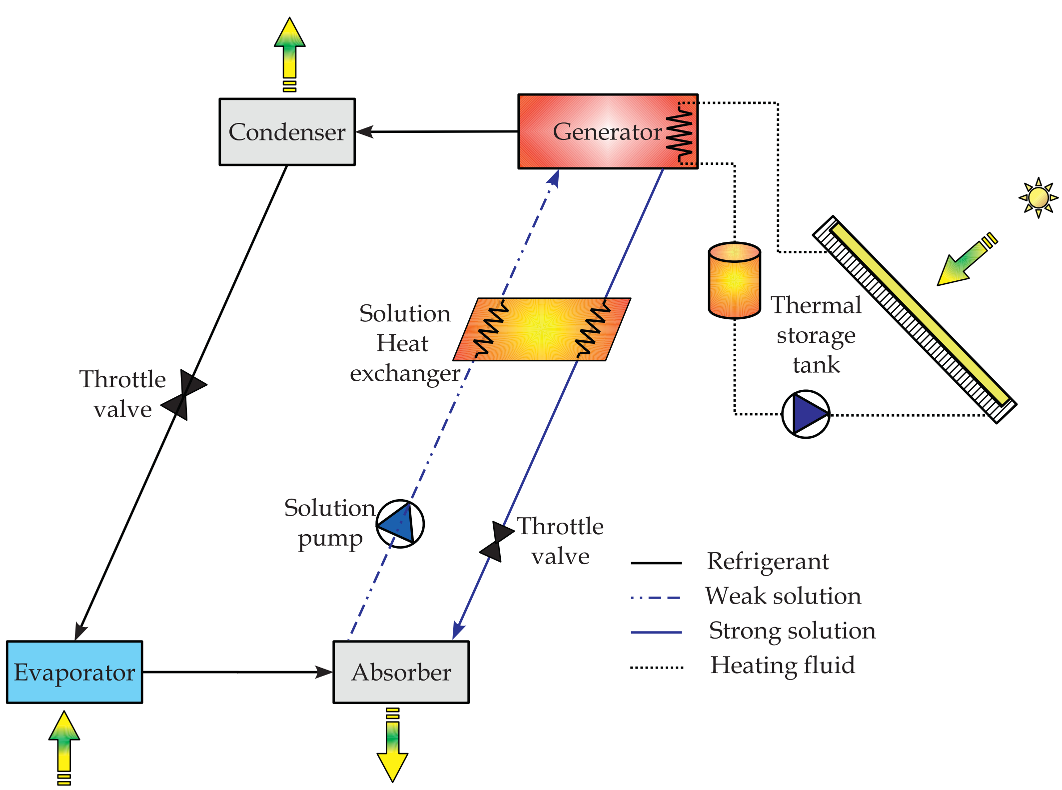

Fig. 1. A schematic diagram for the basic single effect solar absorption cooling system.

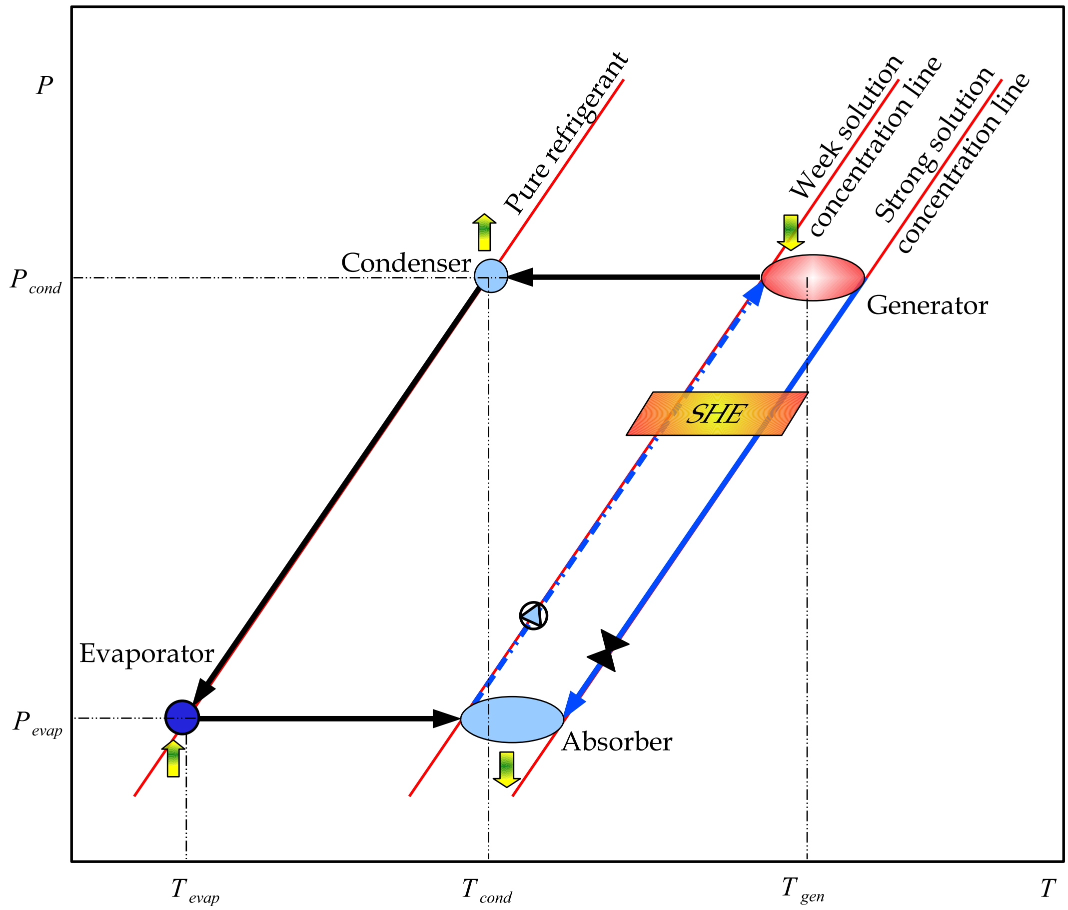

Fig. 2. The *P–T–X* diagram for single effect absorption system, Dühring plot.

collector array with a surface area of 38.2 m^2, a 4.7 kW nominal cooling capacity LiBr–H_2O absorption chiller, a 2.75 m^3 hot-water storage tank, a cooling tower, a fan-coil unit, an electrical auxiliary heater, a data-acquisition system and the associated control systems. The solar fraction and overall system efficiency were assessed and compared to similar systems. It was found that the tested solar air-conditioning system had an annual system efficiency of 7.8% and an average solar fraction of 55%. In [37], a solar plant was installed with a surface area of 440 m^2 of evacuated-tube collectors, a reflecting surface of the same area and an absorption refrigeration system for air-conditioning. A 43 m^3 heat-storage unit, at temperatures of 80-90 °C, and a 150 m^3 cold-storage unit were also installed. Lazzarin et al. [37] reported on two years the data and the analysis for their working system.

Li and Sumathy [18] studied experimentally the performance of a solar powered absorption air conditioning system with a partitioned hot water storage tank. They employed a flat-plate collector array with a 38 m^2 surface area to drive a single-effect LiBr–H_2O absorption chiller of 4.7 kW cooling capacity. The thermal energy produced by the solar collector was stored in a 2.75 m^3 hot-water storage tank, which is partitioned into two parts. The upper part had a volume of about one-fourth of the entire tank. Their experimental results during the summer period showed that the solar COP was 0.07 which is about 15% higher than with traditional whole-tank mode. Experimental results show also that, during cloudy days, the system could not provide a cooling effect. However in the partitioned mode-driven system the chiller could be energized, using solar energy as the only heat source. The work presented by Asdrubali and Grignaffini [38] describes an experimental plant aimed at simulating and verifying the performances of a single-stage H_2O–LiBr absorption machine. The results show that the absorption machine can work, with acceptable efficiency, with input temperatures of about 65–70 °C; this result is interesting for a future supply of the machine with solar energy.

Syed et al. [39] report experimental results derived through field testing of a part load solar energized cooling system for typical Spanish houses in Madrid during the summer period of 2003. Twenty flat-plate collector modules with an absorber area of 2.5 m^2 each were used to energize the system. A single-effect LiBr/H_2O absorption chiller of 35 kW nominal cooling capacity is used. Thermal energy was stored in a 2 m^3 stratified hot water storage tank during hours of bright sunshine. The reported daily average solar cooling ratio (cooling produced divided by incident solar energy) is 11%. Pongtornkulpanich et al. [40] introduced a solar driven 35 kWt LiBr/H_2O single-effect absorption cooling system which is designed and installed at the School of Renewable Energy Technology in Thailand. The chiller is sized to meet 150% of the calculated maximum cooling load. The authors collected data on the system's operation during 2006 and analyzed it to find the extent to which solar energy replaced conventional energy sources. They found that the 72 m^2 evacuated tube solar collector delivered an average yearly solar fraction (solar thermal energy supplied to chiller divided by the total thermal energy supplied to chiller) of 81%. While the remaining 19% of thermal energy required by the chiller was supplied by a LPG-fired backup heating unit.

Rosiek and Batlles [41] analyze the behavior of the solar-assisted air-conditioning system installed in the Solar Energy Research Center (CIESOL) situated in the Campus of University

of Almeria in Spain. This system consists mainly of flat-plate solar collectors with the area of 160 m^2 and a single effect H_2O–LiBr absorption chiller with the cooling capacity of 70 kW. Experimental results during one year of operation show that the solar collectors were able to provide sufficient energy to supply the absorption chiller during the summer mode and sufficient to cover the whole heating demand. The absorption system has an average values of COP about 0.6 with a cooling capacity of 40 kW in summer. Ortiz et al. [42] presented a numerical model of the solar thermal assisted heating, ventilation and air conditioning system in a 7000 m^2 educational building, situated in a high-desert climate, is used to predict performance and optimize control parameters. The solar collector array uses both flat plates and vacuum tubes. This 70 kW absorption chiller is designed to work with hot water supply temperatures in the range from 70 to 95 °C. It is found that the solar cooling assist can reduce the total external cooling energy requirement by between 33% and 43%, the latter result achieved, surprisingly, at lower solar array operating temperatures. In another study, Mammoli et al. [43] checked these predictions against experimental data. They found that the solar cooling system could supply approximately 18% of the total cooling load. This percentage could be increased to 36% by tuning the air handler operation and by improving the insulation in the storage tank.

A domestic-scale prototype experimental solar cooling system based on a LiBr/H_2O has been developed and tested by Agyenim et al. [44] in Cardiff University, UK. The absorption chiller is 4.5 kW and is driven by a 12 m^2 vacuum tube solar collector. That is besides a cold storage tank and a 6 kW fan coil. The system performance, as well as the performances of the individual components in the system, was evaluated based on the physical measurements of the daily solar radiation, ambient temperature, inlet and outlet fluid temperatures, mass flow rates and electrical consumption by component. The average solar coefficient of performance of the system was 0.58 on a hot sunny day with average peak insolation of 800 W/m^2. The experimental results demonstrates the potential use of the new concept of cold store at this scale in cooling domestic scale buildings with chilled water temperatures as low as 7.4 °C. A solar-driven 30 kW LiBr/H_2O single-effect absorption cooling system which has been designed and installed at Institut Universitaire Technologique of Saint Pierre is presented by Praene et al. [19]. The solar collector is composed of 3×3 series evacuated tubes that produce hot water to run the absorption chiller from 8:00 AM to 5:00 PM. The system is both simulated and tested. According to the first field test, the system was sufficient to obtain thermal comfort and the mean air temperature inside the classrooms of about 25 °C. An experimental and simulation analysis of a laboratory single-stage H_2O–LiBr absorption chiller with a cooling capacity of 14 kW has been performed by Bakhtiari et al. [45]. The machine performance, as described by cooling capacity and COP were measured at different temperatures of chilled, cooling and hot water and, different flow rates of cooling and hot water. Results show that the heat pump can adequately operate over a wide range of generator input energy and chilled water temperature and the cooling water flow rate and temperature significantly affect the performance of the machine. The results have also shown that an absorption heat pump (AHP) has almost a constant COP over a large hot water inlet temperature which makes such a device well suited for refrigeration or solar cooling applications.

4.2. Theoretical studies and system simulations

The two main components of a solar absorption cooling system are the solar collector and the absorption heat pump. The system total performance depends mainly on the characteristics of these two components as well as the surrounding environment. The single effect absorption heat pumps have been extensively theoretically analyzed [46–48]. Most of the theoretical work and reported studies on the cycle of this system have investigated the parameters affecting the performance, optimization and design [49,50]. Other authors tried to give an exergy and a second law analysis of the system [10,51–55]. Some other works aimed at investigating new working pairs for the absorption chiller [21,56]. Some commercial software packages have been used to carry out the simulations like the ABSIM software [57,58].

Mathematical models and simulations of different complexity have been developed to simulate and assess the performance and characteristics of the combined solar collector and single-effect absorption cooling machines. New design options of the solar collector module have been developed. Some software packages like TRNSYS and EES were found to be useful for authors to model and optimize their systems in concern. Florides et al. [59] modeled and simulated a LiBr–water 11 kW cooling capacity solar driven absorption cooling machine which could cover the cooling load of a typical model house in Cyprus. The system is modeled with the TRNSYS simulation program to get the optimum system parameters, and the total life cycle cost of a complete system including the collector and the absorption unit. An integrated transient simulation program is developed by Joudi and Abdul-Ghafour [60] for simulating the Iraqi solar house lithium bromide–water absorption cooling system using TRNSYS. The authors concluded that the solar cooling system can be simulated successfully by using TRNSYS with comparable results with actual solar cooling systems. Moreover, using the cooling f-chart and the storage size design chart, or their related equations, simplifies the designer task for predicting the solar fraction for solar cooling systems for any type of building, collector, meteorological conditions and locations.

Various cycle configurations and solar energy parameters for a solar-powered single stage absorption cooling system with a water–lithium bromide solution were simulated by Atmaca and Yigit [61]. The best design choice was a solar collector area of 50 m^2 and a 3750 kg storage tank mass. A solar cooling system that has been designed for Malaysia and similar tropical regions using evacuated tube solar collectors and LiBr/H_2O absorption unit has been introduced by Assilzadeh et al. [62]. The modeling and simulation of the absorption solar cooling system is carried out with TRNSYS program. The typical meteorological year file containing the weather parameters for Malaysia is used to simulate the system. The results presented show that the system is in phase with the weather, i.e. the cooling demand is large during periods that the solar radiation is high. It was shown that, in order to achieve continuous operation and increase the reliability of the system, a 0.8 m^3 hot water storage tank is essential. The performance and cost of a CPVT system with single effect absorption cooling are investigated in by Mittelman et al. [63]. Their results show that under a wide range of economic conditions, the combined solar cooling and power generation plant can be comparable to, and sometimes even significantly better than, the conventional alternative.

Mazloumi et al. [64] simulated a solar single effect lithium bromide-water absorption cooling system in Ahwaz, Iran. The solar energy is absorbed by a horizontal N–S parabolic trough collector and stored in an insulated thermal storage tank. The system has been designed to supply the cooling load of a typical house where the cooling load peak is about 17.5 kW in July. A research project aiming at assessing the feasibility of solar-powered absorption cooling technology under Tunisian conditions was presented by Balghouthi et al. [65]. The simulation was carried out using the TRNSYS and EES programs with

a meteorological year data file containing the weather parameters of Tunis, the capital of Tunisia, were carried out in order to select and size the different components of the solar system to be installed. They found that the optimized system for a typical building of 150 m^2 is composed of a water lithium bromide absorption chiller of a capacity of 11 kW, a 30 m^2 flat plate solar collector area tilted 35 $^\circ$ from the horizontal and a 0.8 m^3 hot water storage tank.

Helm et al. [11] introduced the application of buffering the reject heat of the sorption by the heat storage and transferred to the ambient during periods of low ambient temperatures, night time or off-peak situations. By that means heat rejection of the chiller is shifted to periods with lower ambient temperatures. Calise [66] investigated the energetic and economic feasibility of a solar-assisted heating and cooling system for different types of school buildings and Italian climates. The system under investigation is based on the coupling of evacuated solar collectors with a single-stage LiBr–H_2O absorption chiller. The system was coupled with different types of school buildings located in three different Italian climatic zones. The analysis is carried out by using the TRNSYS software. The results were encouraging in terms of the potential of energy saving. A simulation study to assess the performance of a solar-biomass hybrid single effect LiBr–water absorption chiller suitable for residential applications was conducted by Prasartkaew and Kumar [67]. The chiller and overall system coefficient of performances was found to be 0.7 and 0.55 respectively and the biomass (charcoal) consumption for 24 h operation was 24.44 kg/day. The results of the study indicate that solar-biomass hybrid air conditioning for tropical locations for residential applications is feasible, and can replace conventional vapor compression systems, thus reducing the need for fossil fuel based energy systems for cooling purposes.

The solar cooling system analyzed by Monné et al. [68] consists of 37.5 m^2 of flat plate collectors, a 4.5 kW, single effect, LiBr–H_2O rotary absorption chiller and a dry cooler tower. A novel solar powered air conditioner system is introduced by Al-Alili et al. [69]. The system consists of a hybrid air conditioner and a hybrid solar collector. The hybrid air conditioner consists of a solid desiccant wheel cycle (DWC) which is driven by the collector thermal output and a conventional vapor compression cycle (VCC) powered by the electrical output from the PV panels. The results also show that integrating a DWC with a conventional VCC is more effective than the stand-alone VCC in ensuring comfort of buildings in hot and humid climates. The simple single-effect cycle two restrictions. The first is related to the cycle COP which cannot be raised above a limit in the order of one. The second is related to the temperature of the driving heat which cannot be lowered beyond a certain temperature. However, this can be overcome by multi-staging the single-effect cycle. This is done by repeating either the desorption–condensation processes or the evaporation–absorption processes at different pressures or temperatures as compared to the single-effect cycle [70].

The absorption cooling systems are classified according to the number of effects as well as the number of lifts. Effects refer to the number of times high-temperature input heat is used by the absorption machine. In general, increasing the number of effects is meant to increase the COP using higher driving temperature levels. Lifts refer to the number of absorber/desorber pairs to increase successively the refrigerant concentration in the solution and thus to reduce the required heat input temperature level [15]. There are many designs and different configurations of the multi-effect, multi-lift, and combinations of both absorption cooling systems. The operation of these absorption cycles types already have been described in detail by Herold et al. [71], Ziegler [70], and Ziegler and Alefeld [72]. However, not all of the available absorption cycles types are suitable for application with solar energy. Only those cycles requiring low temperature level can be integrated with the solar collector to provide cold. Absorption machines that are working at temperatures higher than the single effect cycle are unsuitable for solar cooling. The single regenerative cycle was originally devised for solar cooling. It was shown that it can start operation from low temperature and its COP can approach 70% of the Carnot cycle at high generation temperatures [73]. However, recent researches show that there are also configurations other than the commonly used single effect machines for solar absorption cooling. These include the half effect, double effect cycles.

5. The half effect solar absorption cooling system

The half effect cycle, also called two-stage or double-lift cycle, can provide cold with a relatively low driving temperature. A schematic diagram for this cycle is shown in Fig. 3. The COP of this cycle is roughly half of the single effect cycle and so often called half effect. The half effect absorption refrigeration cycle has discussed by Arivazhagan et al. [74] and Gebreslassie et al. [75]. Kim and Machielsen [76] carried out a comparison of various systems in terms of performance and manufacturing cost to investigate feasibility of low-price air-cooled solar absorption cooling system through. They found that half effect systems would require about 40% more heat exchange surface and 10–60% more collector area compared to single effect system of the same cooling capacity. Moreover, the half effect system can yield higher average cooling efficiency than single effect system with the low cost flat plate collector or its comparable types. They concluded that a half-effect cycle would be most promising for air-cooled solar absorption air conditioning in terms of initial solar collector cost. In another work, Kim and Infante Ferreira [77] investigated theoretically a low temperature-driven half-effect LiBr–water absorption cycle combined with low-cost flat solar collectors for solar air conditioning in extremely hot and dry regions. Simulation results predict that the chillers would deliver chilled water around 7 °C with a COP of 0.37 from 90 °C hot water under 35 °C ambient condition.

Sumathy et al. [78] have presented a model and experimental testing for a two-stage lithium bromide absorption solar cooling system in south China. Test results have proved that the two-stage chiller could be driven by low temperature hot water ranging from 60 to 75 °C, which can be easily provided by conventional solar hot water systems. Based on the successes of this system, they integrated the solar cooling and heating system with two-stage absorption chiller and with cooling capacity of 100 kW. Operating results from the system indicated that this type of system could be efficient and cost effective comparing with the conventional cooling system with single-stage chiller. The proposed system with a two-stage chiller could achieve the same total COP as of the conventional system but with a cost reduction of about 50%.

A solar plant, consisting of flat plate collectors feeding the generators of the double-stage LiBr–H_2O air-cooled absorption cycle has been modeled by Izquierdo et al. [79]. Results show that about 80 °C of generation temperature are required in the absorption machine when condensation temperature reach 50 °C, obtaining a COP equal to 0.38 in the theoretical cycle without crystallization problems. In another work, Izquierdo et al. [80] have presented an exergetic analysis for the previously discussed system. The conclusions obtained show that the irreversibilities generated by the double stage thermal compressor will tend to increase with the absorption temperature up to 45 °C. The conclusions show that the double stage system has about 22% less exergetic efficiency than the single effect one and 32% less

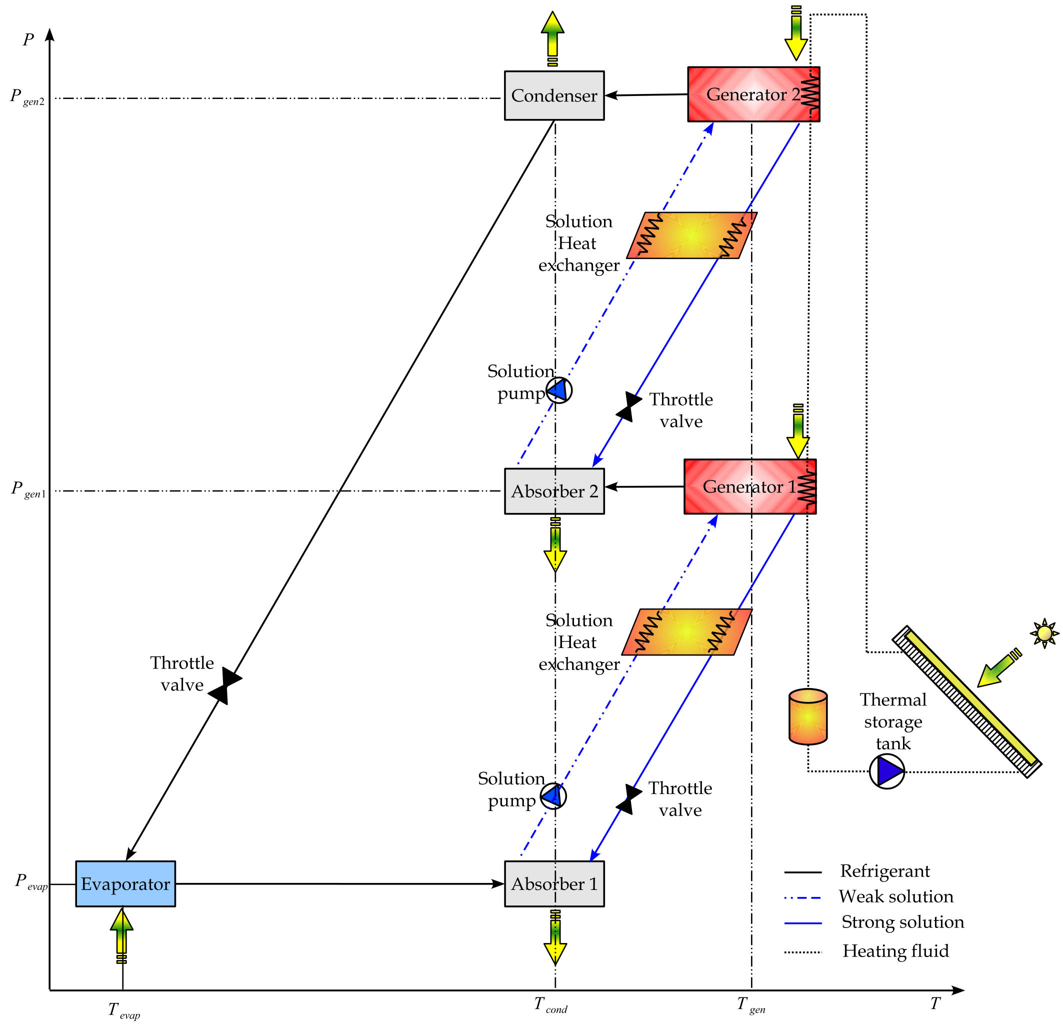

Fig. 3. Schematic for the half effect solar absorption cooling system.

exergetic efficiency than the double effect one. The entropy generated and the exergy destroyed by the air cooled system are higher than those by the water cooled one. For an absorption temperature equal to 50 °C, the air cooled mode generates 14% more entropy and destroys 14% more exergy than the water cooled one.

Figueredo et al. [81] have analyzed the behavior of a water–LiBr double-stage absorption chiller with 200 kW of cooling power. The modeled machine can operate in summer as a double-stage chiller driven by heat at 170 °C from natural gas, as a single-stage chiller driven by heat at 90 °C from solar energy, or simultaneously in combined mode at both temperatures. It can also operate in winter in double-lift mode for heating with a driving heat at 170 °C from natural gas.

6. The double effect solar assisted absorption cooling systems

Double effect system can be achieved by adding an extra stage as a topping cycle on the single effect cycle. Absorption chillers based on the double-effect technology offer the potential for a more effective conversion of solar energy and less primary energy use. They have a double COP value compared with that of single effect systems, nearly 1.2. However, their working liquids must achieve higher temperatures, more than 130 °C, which is beyond the range for which most solar collectors are designed. As shown in Fig. 4, the high pressure generator is driven by conventional energy and natural gas. Solar energy together with water vapor generated in the high pressure generator supply energy to the low pressure generator. The temperature of hot water supplied to the low pressure generator is close to 90 °C. Many researchers have studied and analyzed the double effect absorption cooling machines [82–86]. However, few studies related to the solar driven or solar assisted double effect absorption chillers were found in the literature.

Liu and Wang [9] presented the performance prediction of a solar/gas driving double effect LiBr–H_2O cooling absorption system with a cooling capacity of 10 kW. This system uses solar energy as part of energy supply together with gas burning in the high-pressure generator. This system will serve for cooling and heating all over the year. Simulation results illustrate that this kind of system is feasible and economical. In his study, Tierney [87] performed a comparison among four systems with different chiller–collector combinations and at four different latitudes. The other main objective was to identify the combination that has the largest savings in primary energy for refrigeration demands of 50 or 100 kW. It is demonstrated that the combination of a trough collector with a double-effect evaporator is particularly effective.

A smallest high temperature solar thermal cooling and heating system at Carnegie Mellon University in Pittsburgh, PA was studied by Qu et al. [88] through its design, installation, modeling, and evaluation. This system comprised a 52 m^2 of linear parabolic

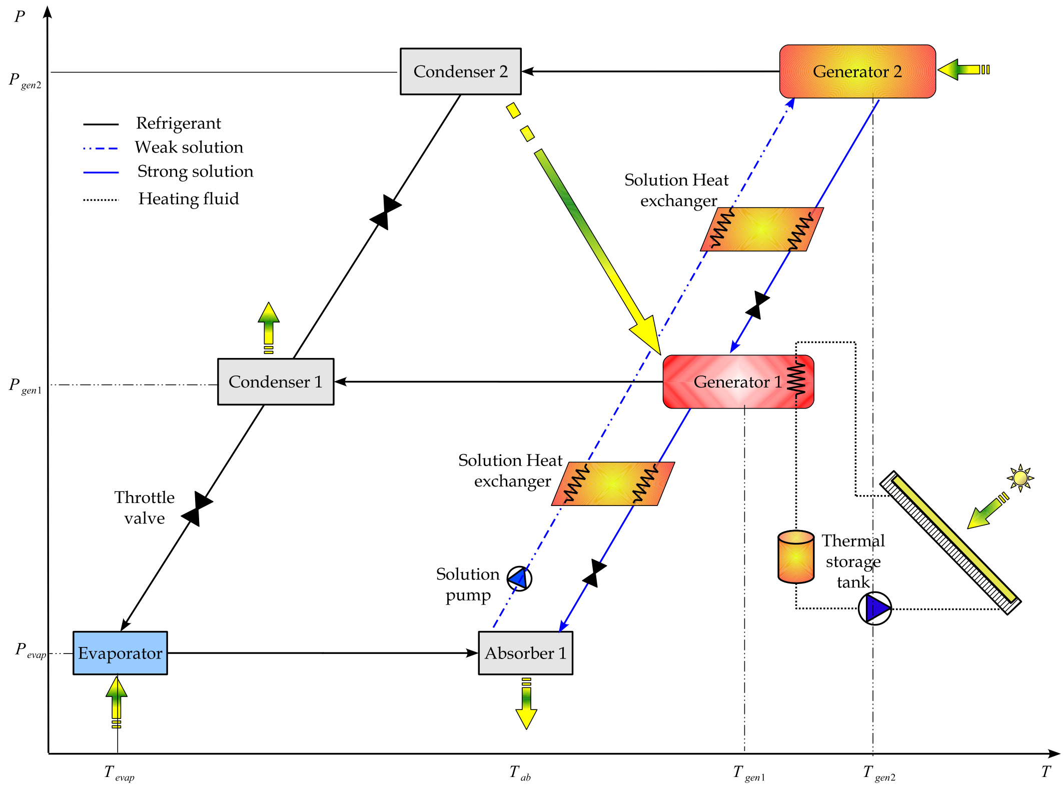

Fig. 4. Schematic for the double effect solar assisted absorption cooling system.

trough solar collectors and a 16 kW double effect water–lithium bromide absorption chiller. The absorption chiller was a dual natural gas burner to provide heat when solar energy was inadequate and is integrated with a cooling tower as well. Performance of the system has been tested and the measured data were used to verify system performance models developed in TRNSYS. It was found that the solar COP of the overall installed solar cooling system was about 0.33–0.44 with the possibility to supply 39% of cooling and 20% of heating energy for the building if it included a properly sized storage tank and short, low diameter connecting pipes.

7. The intermittent solar absorption cooling cycles

In this type of solar driven adsorption refrigeration cycles, the cold production process is not continuous and occurs only at night times. This type of refrigeration technology has been utilized for food preservation rather than comfort cooling. The intermittent cycle may work based on the single or the double stage technology. In an intermittent absorption system, there is no any moving part because the solution pump is eliminated and the density difference is utilized for the solution circulation based on the thermosiphon principle. Moreover, no auxiliary heater in the system and the cycle is purely derived by solar energy. The solar collector is used as a generator during day times and as an absorber during the cooling production at night times. Ammonia–water is generally used as the refrigerant/adsorbent pairs in this type of systems. The intermittent solar absorption cooling system has two configurations: the first is a single stage and the second is a two stages configuration. Here, "two stages" distinctly refers to stages of generation, namely, high pressure generation and low pressure generation. The STR of the single stage intermittent systems at a generating temperature of 120 °C is about 0.0525. Whereas, the overall COP of the two stage system operating at this temperature is 0.105, which is twice that of a single stage system operating at 120 °C. Thus a two stage system operating at low generation temperature is better than a single stage system operating even at high temperature [89].

7.1. The single stage intermittent cycles

A schematic diagram of the basic single effect intermittent solar absorption cycle is shown in Fig. 5. The working principle of this system was introduced by Venkatesh and Mani [89].

Staicovici [90] described an intermittent single-stage H_3O/NH_2 solar absorption system of 46 MJ/cycle. He used evacuated solar collectors with selective surfaces to heat the generator. It was found that the system coefficient of performance varies between 0.152 and 0.09 in the period of May–September. Actual system COP values of 0.25–0.30 can be achieved at generation and condensation temperatures of 80 °C and 24.3 °C respectively. For bigger capacities of 450–675 MJ/day, the pay-off period is estimated to be 6 and 4 years respectively and the life-time to 15-18 years.

A solar cooling machine has been built for demonstration purposes by Erhard and Hahne [30]. The main part of the device is an absorber/desorber unit which is mounted inside a concentrating solar collector. Performance of the solar refrigeration unit was measured in a field test. The working principle of a periodically working, dry absorption cooling machine will be explained using the demonstration machine as an example. A simulation program for the numerical simulation of a solar-powered dry absorption cooling machine has been developed and tested. The overall COP of the cooling system was 0.049. Experimental and theoretical analysis were performed under real field conditions in Delhi on solid–vapor intermittent solar absorption chilling system by Bansal et al. [33]. This system is designed and fabricated by a German Firm, named DORNIER. The solar thermal energy is supplied by heat pipe vacuum tube solar collectors through thermosyphonic flow of water.

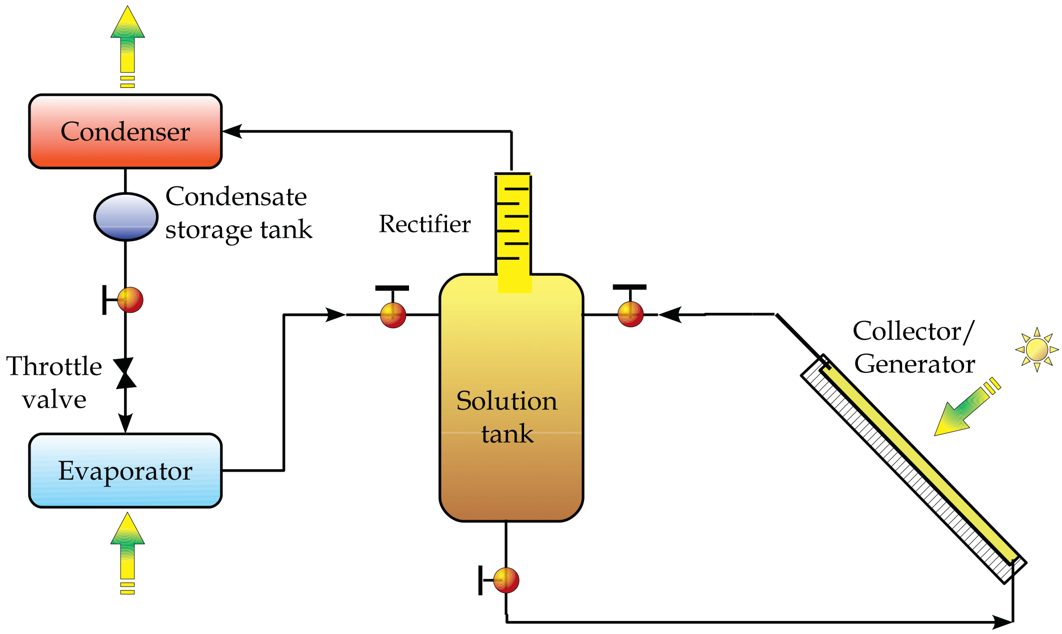

Fig. 5. The single stage intermittent solar absorption cooling system.

The unit has 1.5 kW h/day cooling capacity and uses ammonia as a refrigerant and IMPEX material, which is composed of 80% $SrCl_2$ and 20% graphite and has high heat and mass transfer coefficient as well as high absorption capacity, as absorbent.

A solar powered discontinuously working solid sorption cooling machine with no moving parts has been built for demonstration purposes at the Institut für Thermodynamik und Wärmetechnik by Erhard et al. [91] and Erhard and Hahne [30]. The working pair consists of NH_3 used as the refrigerant and $SrCl_2$ as the absorbing medium. The absorber/desorber unit is mounted inside a concentrating solar collector. The performance of the solar refrigeration unit was measured in a field test. Furthermore, a simulation program for the numerical simulation of the machine has been developed and tested. The overall efficiency of the cooling system has been calculated as 0.04, using the data from the year 1994. In 1995, several improvements were made to the system, so that a better overall efficiency of 0.05–0.08 was reached. The theoretical performance of an intermittent absorption refrigeration system operating with the ammonia/lithium nitrate ($LiNO_3$) mixture reported was reported by Rivera and Rivera [31]. A compound parabolic concentrator (CPC) with a glass cover operates as the generator–absorber of the cooling system. The results showed that the theoretical efficiencies of the CPC were 0.78 to 0.33 depending on the time of the day and the season. It was possible to produce up to 11.8 kg of ice at generation temperatures of around 120 °C and condensation temperatures between 40 °C and 44 °C allowing the system to be cooled with air or water. The overall efficiencies of the system were between 0.15 and 0.4 depending on the generation and condenser temperatures.

A solar intermittent absorption refrigeration system for ice production is developed in the Centro de Investigación en Energía of the Universidad Nacional Autónoma de México by Rivera et al. [92]. The system consists of a cylindrical parabolic collector acting as generator–absorber and operates with the ammonia/lithium nitrate mixture with a nominal capacity of 8 kg of ice/day. The evaporator temperature obtained for several hours with solar coefficients of performance up to 0.08 was -11 °C. It was found that the coefficient of performance increases with the increment of solar radiation and the solution concentration. Also it was found that with an increase of the solution concentration, the maximum operating pressure increases meanwhile the generation temperature decreases. Another study is presented by Moreno-Quintanar et al. [93] for the same system using ammonia/lithium nitrate ($NH_3/LiNO_3$) and ammonia/lithium nitrate/water ($NH_3/LiNO_3/H_2O$) mixtures. Several test runs were carried out at different solution concentrations for these two mixtures. Evaporator temperatures of -8 °C was obtained for a time period of 8 h. Comparing the performance of the system operating with the two mixtures, it was found that with the ternary mixture the solar coefficients of performance can be up to 24% higher than those obtained with the binary mixture, varying from 0.066 to 0.093.

The problem in the single-stage system is that it may sometimes fail to operate due to some reasons [89]. First, when the maximum generation temperature is low and tends to that at state 2 in Fig. 5, the system fails as no or very little ammonia is generated. Second, for the same first reason the system fails to operate when the condenser temperature is high for a given generation temperature. Third, the system fails to operate if the demanded evaporator temperature is less than that at state 7 in Fig. 5. The first two cases may arise from climatic changes and the third has a direct bearing on the requirements. The above mentioned problems can be overcome by resorting to a two-stage system [94].

7.2. The two stages intermittent cycles

The two-stage intermittent system can be used to improve the operation and enhance the efficiency of the single stage system. Moreover, it can solve the limiting operation temperature in the single stage system. In the two stage system there are two levels of generator pressures, a high-pressure generator (HPG) and a low-pressure generator (LPG). The HPG and LPG generators are sets of flat plate collectors. The generators are built into the flat plate solar collector. As shown in Fig. 6, there are two weak solution storage tanks (Tank 1 and Tank 2) to store and supply to HPG and one tank (Tank 3) to store and supply the weak solution to LPG. Tank 1 and Tank 2 do not supply the weak solution to HPG at the same time; they alternate daily. Tank 3 is operated every

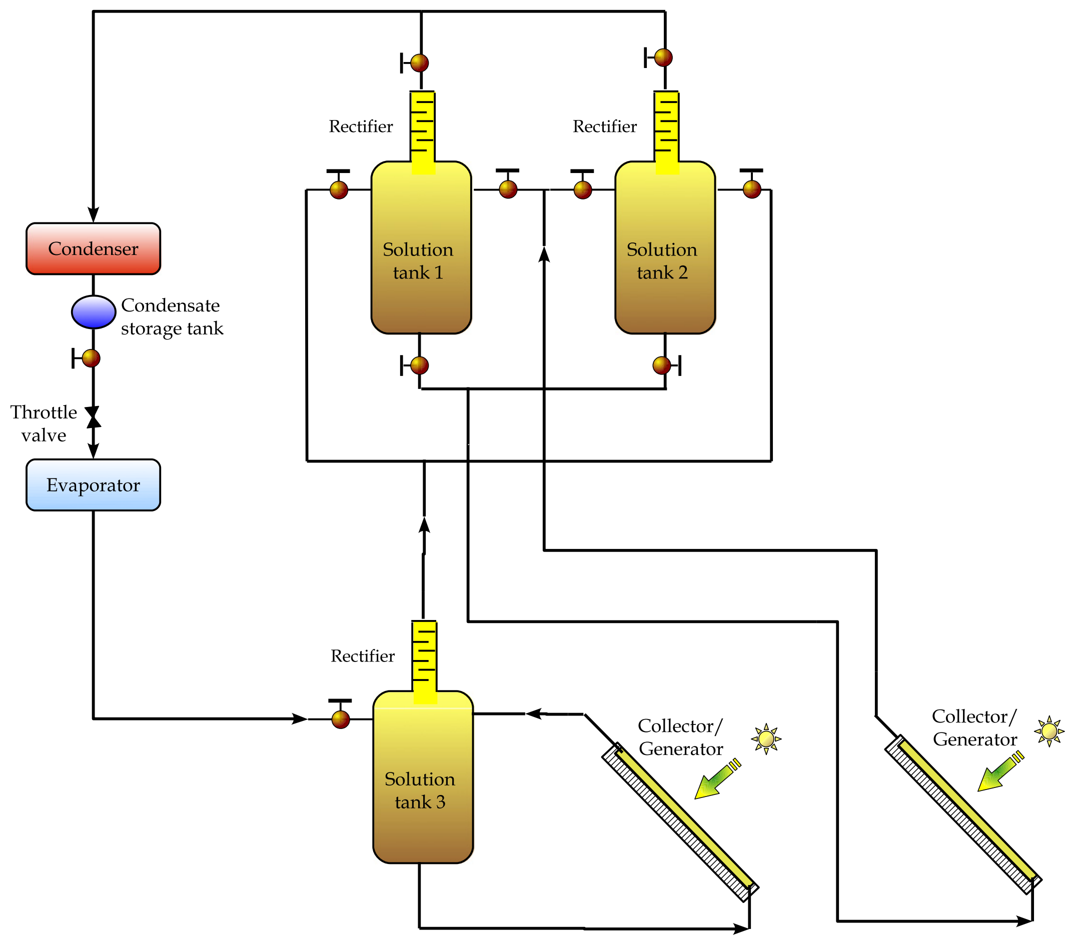

Fig. 6. Construction of the two stage intermittent solar absorption cooling system.

day to supply the weak solution to Tank 1 or Tank 2, whichever is not supplying solution to HPG [95].

A two stage intermittent solar refrigeration system is studied by Mani and Venkatesh [94]. The authors aimed to evaluate the proper values for the low and high pressure stage initial solution concentrations and volume ratio of low pressure to high pressure generator through the relevant thermodynamic analysis. In their analysis they assumed that both generators will have around the same temperature because they are heated through flat-plate solar collectors. They found that at the concentration of 0.6 the two generator temperatures are around the same value. Hence, from the operational point of view, 0.6 appears to be the right initial solution concentration in the high pressure generator.

Another study was accomplished by Das and Mani [96] on a two stage intermittent solar refrigerator. They tried to find the best absorbent fluid that for the R22 refrigerant, which is a popular choice as refrigerant for its ozone friendliness (ODP=0.05). The working fluids used in their study for the comparison are R22-DMF (*N*,*N*-dimethyl formamide), R22-NMP (*N*=methyl,l-2-pyrolidone) and R22-DMETEG (dimethylether tetraethylene glycol). They find that the best working fluid comes out to be R22-DMF.

8. The diffusion absorption solar cooling system (Platen–Munters cycle)

A special kind of absorption cooling cycle was developed in 1922 by the two Swedish engineers, Platen and Munters. The cycle is so called as Platen–Munters cycle and the machine is called the diffusion absorption refrigeration (DAR) system. The main distinctive feature of the DAR machine is the lack of pumps or any moving parts that require auxiliary energy supply. Therefore, the system is noiseless and free from vibration. Moreover, it exhibits good reliability, durability, and minimum maintenance costs [97]. The whole unit has the same total pressure and as a consequence, the usual throttling required for the pressure reduction is removed and the solution pump can be a simple gas bubble thermally powered pump. Fig. 7 shows a schematic diagram for the DAR machine and its main components. The main components of the DAR system are the generator, condenser, evaporator, absorber, rectifier, and a bubble pump that is besides the auxiliary gas heat exchanger (AGHX) and solution heat exchanger (SHX). The cycle uses a three-component working fluid consisting of the refrigerant, the absorbent, and the auxiliary gas. Ammonia is generally used as a refrigerant, water is used as an absorption media and the auxiliary gas is a kind of inert non-condensable and non-absorbable gas like hydrogen or helium. The main reason for using an auxiliary inert gas in the DAR cycle is to maintain a constant total pressure in the whole system. The principle of the cycle operation is similar to the single stage absorption cycle. The difference is that the total pressure is the same in the entire system. Ammonia circulates through all the system components. Water–ammonia solution circulates through the generator, gas bubble pump, and absorber. The ammonia–hydrogen gas mixture circulates in the auxiliary gas circuit which includes the evaporator, absorber, and gas heat exchanger (not shown in figure), and is driven by natural convection. The generator temperature varies typically between 120 and 180 °C,

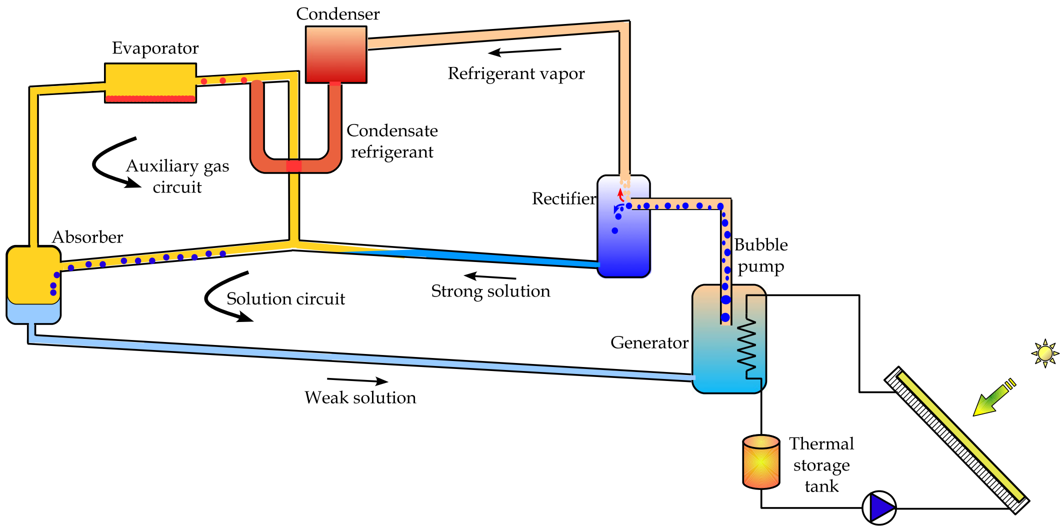

Fig. 7. The diffusion absorption solar refrigeration system.

and the practical COP varies between 0.2 and 0.3 with cooling capacity of 25–100 W. However, large capacity systems are not considered as attractive.

The ammonia rich solution coming from the absorber is heated in the generator-bubble pump device. The bubble pump forms ammonia vapor bubbles, which push liquid up in the small-diameter vapor-lift tube providing the liquid circulation in the cycle. In the rectifier, ammonia vapor is separated and flows towards the condenser and a strong solution is formed and flows to the absorber by gravitational effect. Then the vapor is condensed at the air cooled condenser and the ammonia liquid flows towards the evaporator. The refrigerant partial pressure is allowed to be low in the evaporator, achieving the refrigeration effect. The refrigerant condensate is exposed to the hydrogen atmosphere in the evaporator. The cooling effect is achieved when liquid ammonia evaporates due to its low partial pressure and forming ammonia–hydrogen gas mixture that leaves the evaporator and flows towards the absorber after passing through the internal heat exchanger. The strong absorbent in the absorber attracts the refrigerant while the auxiliary non-absorbable gas returns back in counterflow towards the evaporator after passing through the internal heat exchanger. Hydrogen is circulated between the evaporator and the absorber, compensating for the pressure difference between the high and low pressure side. The auxiliary gas circuit loop is driven by natural convection caused by the density differences associated with the ammonia composition in the gas phase.

Several scientific research efforts undertaken to study and improve the current cycle performance of the diffusion absorption refrigerator system. Some theoretical studies were introduced by authors who have presented the mathematical and thermodynamic modeling to investigate the performance of the DAR system [97–102]. Others have conducted the experimental work and testing on the DAR machine [103–105]. However, few papers have been published regarding the application of the solar powered DAR machine.

Gutiérrez [26] presented a study on the thermal performance of a solar refrigerator that was developed from a commercial absorption diffusion type. The refrigerator that had a flat plate collector substituted for its burner and ammonia–water solution and hydrogen was used in the system. Since there is no hot thermal storage to operate the system continuously, cooling occurs during daytime only. The heat is rejected by natural air convection. A series of experiments was performed in which the system was solar powered and also operated in a solar simulator, in order to know the effects of the ambient temperature on the behavior of the apparatus. According to experimentation and testing results, it was found that under good insolation conditions, the refrigerator maintains freezing temperatures during 5 h a day, provided that the ambient temperature does not exceed 28 °C.

A Platen–Munters refrigerator has been modified by Valizadeh and Ashrafi [106] to operate with heat collected from solar energy continuously. This was done through the use of a solar storage battery coupled to a fast response heat pipe for the transfer of the stored energy to the refrigerator. The storage system is a well insulated storage tank containing a special type of oil which is nondegradable in the operating temperature of about 200 °C. The results of the experimental work show that the cooling action started after the system was exposed to 90 min of solar radiation and temperature of as low as −10 °C was being achieved in the ice box. Jakob et al. [27] presented experimental analysis and simulation of a solar heat driven ammonia/water (NH_3/H_2O) diffusion–absorption cooling machine. The designed cooling capacity of the machine is 2.5 kW for air-conditioning applications. The maximum COP reached was 0.38. Helium is proved to be preferable to hydrogen as auxiliary gas for the cycle. The diffusion–absorption cycle was modeled using an expanded characteristic equation of sorption chillers. The simulation model showed good agreement with the measured data.

Ben Ezzine et al. [107] presented an experimental investigation of an air-cooled low capacity 50 W thermal driven DAR machine. The system was operating with a binary light hydrocarbon mixture (C_4H_{10}/C_9H_{20}) as working fluids and helium as pressure equalizing inert gas. The machine is intended to be solar powered heat from flat plate or common evacuated tube collectors. The experimental results show that for a bubble pump heat inputs from 170 to 350 W, the driving temperature varies in the range of 120–150 °C. The lowest temperature reached at the evaporator entrance is −10 °C provided by a driving temperature 138 °C. The optimal COP is 0.175, corresponding to heat input of 265 W and a heat source temperature of near 140 °C. In another work, Ben Ezzine et al. [108] investigated by numerical simulation the feasibility of a solar driven DAR using the mixture R124/DMAC as working fluid. They tried two cooling medium temperatures in their simulation, 27 °C and 35 °C, and four driving heat temperatures in the range from 90 °C to 180 °C for a design cooling capacity of 1 kW.

9. The solar open cycle absorption cooling system

The closed cycle absorption refrigeration systems require heat source temperatures that are significantly higher than the temperatures of corresponding condenser. The solar powered open cycle absorption cooling system is a promising alternative that has received much attention due to the outstanding characteristic of this system, which is the absence of condenser. In an open absorption cooling system, flows of heat and mass take place to and from the system at relatively low temperatures of the heat source. The entire operation takes place at atmospheric pressure, thus eliminating the need for vacuum vessels. Water is generally used as the refrigerant in this system. The reason is that the refrigerant is released to the ambient atmosphere and therefore it should be environmentally friendly. Another reason is the requirement of a continuous supply of make-up refrigerant during the entire operating time. As a consequence, water as a refrigerant is very suitable working fluid in the open cycle absorption cooling system. Absorbents like LiBr, LiCl or $CaCl_2$ are usually used with water refrigerant.

In the open cycle absorption cooling system, one can have two possible options depending on whether the absorption system is made open from the regenerator part or from the evaporator part. The first option is the open regeneration absorption cooling system, where the system is made open to the regenerator side. The second option is the open evaporative cooling system, in which the system is open to the evaporator part [109]. These two systems are discussed in the following sections.

9.1. The open regeneration absorption cooling system

This type of open absorption cooling system is open to the regenerator side. A schematic diagram of the solar-operated open absorption refrigeration system is shown in Fig. 8. In this type of cooling machines, the dilute absorbent solution is heated and subsequently re-concentrated in the solar collector, which is open to the atmosphere, due to the evaporating process. The strong regenerated solution leaves the collector and passes through a liquid column, to allow the strong solution to drop from atmospheric pressure to the reduced evaporator pressure. The strong solution then goes to the absorber after passing through a regenerative heat exchanger. In the absorber, the strong solution absorbs water vapor from the evaporator and therefore the latent heat of vaporization of the refrigerant is taken allowing a low temperature in the evaporator space by a vapor absorption process. The resultant weak solution is pumped from the absorber back to atmospheric pressure through the regenerative heat exchanger then through the regenerator to completing the cycle.

An important feature of this system is the unique relationship between the collector/regenerator performance and the system performance. The useful energy output of the regenerator is the evaporation of water, and the useful energy output of the overall system is also the evaporation of water at the evaporator of the system. For every 1 kg of water evaporated in the collector/regenerator at ideal conditions, 1 kg of water can be evaporated in the evaporator and absorbed in the absorber. The rate of water evaporation from the regenerator determines the amount of water which can be evaporated at the evaporator. This gives the cooling capacity of the system, after being multiplied by the latent heat of vaporization of water. Therefore, the study of designing the regenerator part of the open regeneration absorption cooling system becomes most important and necessary to select the most efficient design of the regenerator for optimum performance of the cooling system [109].

The solar collector/regenerator has a great effect on the performance of the system. Its objective is to absorb solar irradiance and generate the strong absorbent solution from the absorbate rich solution by evaporation of the refrigerant. Earlier work by the authors included theoretical simulations and preliminary experiments on the key components of the system with an emphasis on the collector/regenerator performance. The forced flow regenerator is free from the problems of contamination due to dirt and rains. The potential problems with the forced flow regenerator are an additional power requirement for the air blower. Besides, given a reasonable amount of water desorption rate, the introduction of a forced dry air bubbling concept can further enhance the system performance. The open surface regenerator is simple in design and inexpensive. However, mixing of dust or dirt from the air with the absorbent solution in the regenerator is a problem. A brine-still solar regenerator (though not so efficient) is free from these problems and also conserves refrigerant during its operation [110].

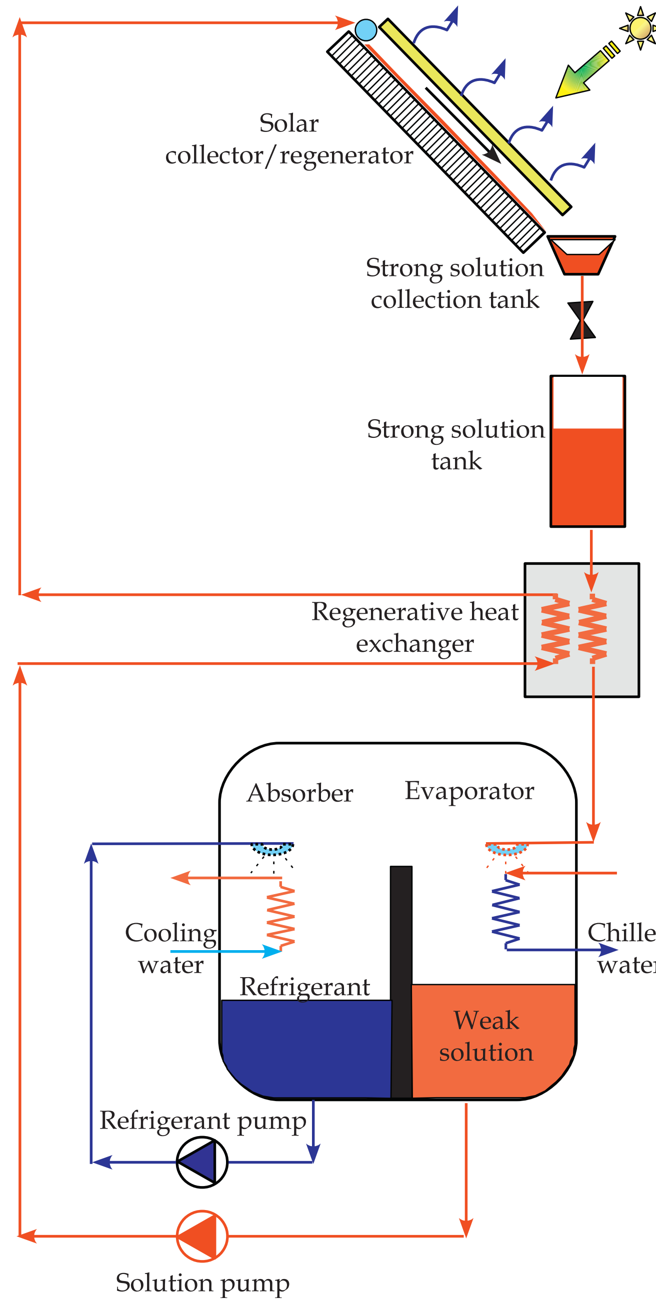

Fig. 8. The solar powered open regenerative absorption cooling system.

An open cycle regenerative absorption refrigeration system and driven by solar energy is simulated and analyzed by Collier [111]. The system performance was simulated for five cities using actual weather data. From the investigation, it was found that the relationship between the collector length and the solution mass flow rate was tied to environmental factors such as wind and humidity when optimizing system performance. Moreover, overall daily cooling COP's (cooling/incident solar) ranged from 0.09 to 0.45 for various conditions. Kumar and Devotta [112] described a mathematical model of a solar regenerator of an open cycle absorption cooling system. The effect of variation of the values of various parameters, like air velocity and total solar insolation, on the performance of the regenerator has also been analyzed. The model has been validated by experimental data from the published literature. They found that the rate of water evaporation increases as the air velocity is increased and as the total solar insolation is increased.

The performance of two collector/regenerator combinations were studied and tested side-by-side under the meteorological conditions of Tempe, Arizona by Hawlader et al. [113]. One of the regenerators was glazed and the other was unglazed. The performance of the collector/regenerator was expressed in terms of the quantity of water evaporated from it, which in effect was a measure of the cooling capacity of the system. The authors found that unglazed regenerator performed better than the glazed one under the same climatic conditions considered. Moreover, the glazed regenerator was found less sensitive to changes in independent variables and its regeneration efficiency was, on the average, 7.6% lower than the unglazed regenerator. Haim et al. [114] described a performance analysis of two open-cycle absorption systems for solar cooling using. The open part of the cycle is in the regenerator and LiCl–H_2O is used as working fluid. One of the systems under study has employed direct regeneration in a regenerating collector, exposing the solution simultaneously to the sun and to a stream of air. The other has employed indirect regeneration by contacting the solution with air heated elsewhere in a flat-plate collector. Results indicate a definite performance advantage of the direct-regeneration system over the indirect-regeneration one.

Yang and Yan [115] presented a computer simulation study for an open cycle absorption solar cooling system opened from the generator side and operates in a humid area. The system with a glazed solar collector/regenerator shows sufficient solar regeneration capacity for operation in Kaohsiung, Taiwan. The simulation of the system was done using average local weather data. Results showed that the solar system can provide 75–97% of the cooling load needed for the summer season under various operating conditions. In another work aimed to determine the optimum glazing height of a glazed solar collector/regenerator was reported by Yang and Wang [116]. An analysis based on experimental data obtained at the National Sun Yat-Sen University, Kaohsiung, Taiwan, under a humid climate is conducted. Based on the analysis, the optimum glazing height is found to be 0.07 m. The authors concluded that the optimally glazed solar collector/regenerator performs better than an unglazed unit for hot humid climates. An extension of this work was conducted by Yang and Wang [117].

An experimental work as a part of continuing investigation onto the concept and operation of an open cycle regenerative absorption cooling system has been conducted at the Faculty of Engineering, El-Mansoura University in Egypt by Sultan et al. [118]. The main objective was to study the effect of inlet parameters on the rate of evaporation of water vapor from the regenerated solution of $CaCl_2$ as a liquid desiccant. The inlet parameters considered in the investigation are the inlet air temperature, solution flow rate, solution inlet concentration, air flow rate and humidity of inlet air. A packed tower for the regeneration of liquid desiccant is used. A total of 110 experimental data sets were taken under various operating conditions. From the results it was found that an increase of 360% air flow rate results in 11% increase in the solution output temperature. The authors concluded that the regeneration process is highly dependent on the air inlet temperature, humidity, and flow rate. In another study, Hamed [119] investigated theoretically and experimentally the regeneration process of a liquid desiccant of calcium chloride by using a packed porous bed consisting of granules of burned clay as a desiccant carrier. In the theoretical model, the transient gradient of air stream parameters, humidity and temperature, as well as desiccant concentration in the bed are defined. In the experimental study, transient concentration gradient in the bed is evaluated by weight method. The regeneration process is intended to be driven by heat from the solar collector. Concentration gradient in the bed is found highly dependent on the mass transfer rate.

Alizadeh and Saman [120] developed a computer model to study the thermal performance of parallel or counterflow to the solution in a solar collector/regenerator using calcium chloride ($CaCl_2$) as the working desiccant. The absorber plate of the collector /regenerator is blackened and glazed to enhance the solar energy absorption and protect it from the environment. A parametric analysis of the system has been performed to calculate the rate of evaporation of water from the solution as a function of the system variables and the climatic conditions. From the performance predictions, it was determined that the water evaporation rate from the weak solution depends on regenerator length, solution mass flow rate and concentration, air Reynolds number and the climatic conditions.

The regeneration of liquid solution using forced cross flow of air stream with flowing film of desiccant on the surface of a solar collector/regenerator has been investigated by Kabeel [121]. The results showed that the forced convection cross flow solar regenerator is of higher efficiency than the free convection regeneration. Moreover, the mass transfer coefficient for the forced unit used in this work is much higher than the free convection unit. The modeling and simulation of the regenerator of the solar driven regenerative open absorption cooling cycles is presented by Zeidan et al. [122]. In this system, calcium chloride ($CaCl_2$) is applied as the working desiccant. They integrated the solar radiation model with the desiccant regenerator model to produce a more realistic simulation. The effect of the regenerator length, desiccant solution flow rate and concentration, and air flow rate, on the performance of the system is studied. They reported that the vapor pressure difference has a maximum value for a given regenerator length. Moreover, for specified operating conditions, a maximum value of the coefficient of performance occurs at a given range of air and solution flow rates. They recommended selecting the design parameters for each ambient condition to maximize the coefficient of performance of the system. In a second work by the same group, Aly et al. [123] investigated the performance of the same system but with the lithium chloride (LiCl) as an absorber. In a third paper of the same authors, Aly et al. [124] presented the modeling and simulation of the same previously described system with the input heat estimated via a real-time solar radiation model.

9.2. The open evaporative absorption cooling system (liquid desiccant system)

This type of solar absorption cooling technologies is open to the ambient from the evaporator part. It is based on open cycle dehumidification–humidification processes. The major components are absorber, regenerator and evaporative cooler which also includes heat exchangers and mass exchangers for dehumidification.

The humid air either from outside or from the building is passed through the liquid absorber. By absorbing the moisture in a liquid desiccant a dehumidified air is produced. Then the produced dry air is passed through the water filled evaporator for sensible cooling. The processed air is then delivered to the space to be cooled. This system is more suitable in hot and humid climates or coastal regions. However, this is an industrial process of cooling, and a large space is required. Many cycles have been proposed.

An investigation of an evaporative cooling open cycle absorption heat pump that is capable of utilizing low grade heat sources such as solar heat as its source of power was reported by Hellmann and Grossman [125]. The system, referred to as dehumidifier–evaporator–regenerator (DER) cycle, operates at atmospheric pressure and its immediate application is for cooling and air conditioning. A computer simulation of the cycle was conducted by the authors and the performance characteristics were determined for a wide range of operating conditions. Moreover, the influence of various design parameters was investigated as well. The cycle operated under design point conditions yields a COP of 0.43 and a cooling capacity of 21.58 kW. The following other work that was accomplished by Pohl et al. [126] was a modification on the DER cycle. The researchers have presented two basic configurations of the DER absorption chiller depending on the air circuit in the system. The first is the open configuration and the second is the semi-open configuration, Fig. 9. Computer simulations of the two configurations operated under ambient conditions of a typical summer day have been conducted. The authors found that the semi-open configuration proved to be superior for most cases with respect to the coefficient of performance (COP). However, under typical summer day conditions, the open DER cycle performed better for chilled water temperatures above 15 °C with the COP attains values of about 0.8. The research on the DER system has been continued by Gommed et al. [127], where they aimed to construct a laboratory system based on an aqueous solution of lithium chloride as the absorbent to test the concept, identify problems and carry out preliminary design optimization for the DER machine. The characteristic performance of individual components, that were analyzed theoretically in the simulation, was studied experimentally. The performance of the system has been studied under varying operating conditions. Gommed and Grossman [128] constructed and installed a 16 kWt capacity solar driven open cycle absorption prototype of the DER system. The system is coupled to a solar collector field and employs two methods of storage - hot water and desiccant solution in the regenerated state. The objectives were to monitor the performance, identify problems and carry out preliminary design optimization for the performance parameters of this prototype. The data analysis indicates a thermal COP of about 0.8, with parasitic losses on the order of 10%.

A liquid desiccant evaporative cooling system powered by solar energy with energy storage was proposed by Kessling et al. [129]. The dehumidified air was cooled by the evaporation of water in order to create a desired temperature. For a high energy storage capacity a high air to solution mass ratio is required to achieve great differences between salt inlet and outlet concentrations.

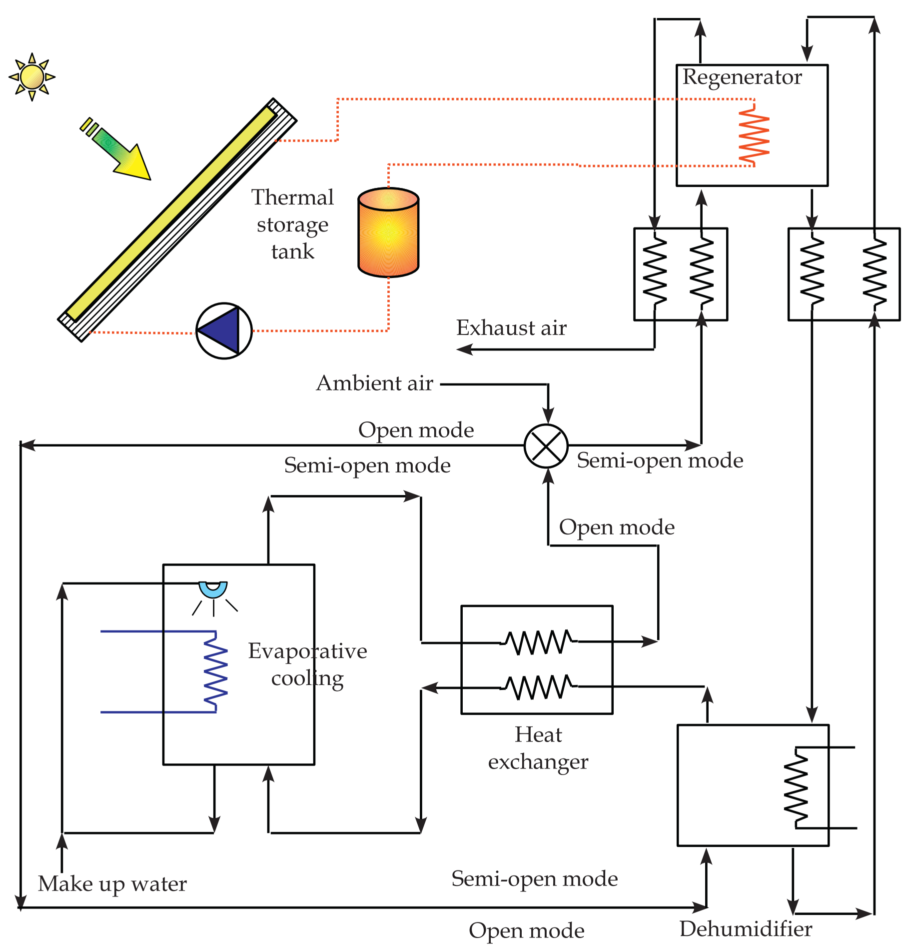

Fig. 9. The dehumidifier–evaporator–regenerator (DER) cycle [125].

10. The hybrid solar absorption cooling systems

Kaushik and Yadav [130] have presented two designs for a hybrid double-absorption solar cooling system. These are: a conventional closed-cycle and open-cycle absorption systems with an additional open-absorber component through which the process room air is passed, cooled and dehumidified. The cooling produced in the evaporator is utilized to remove heat from the open absorber and the process air being circulated. A comparative study of the open and closed cycle options has been made. It is concluded that the hybrid double-absorption solar cooling systems are better in performance than conventional systems and an open-cycle double-absorption system is even more attractive and cost effective as compared to closed-cycle option.

An experimental study was carried out by Sierra et al. [28] in order to demonstrate the technical feasibility of powering an absorption refrigerator by a salinity gradient solar pond. A hot oil at a temperature not higher than 80 °C was used to simulate the heating of the generator by a solar pond. An experimental model of an absorption refrigerator, using ammonia–water solution at 52% concentration by weight, was run intermittently using this heat. Seven complete refrigeration cycles were carried out, with generation temperatures around 73 °C and evaporation temperatures around -2 °C. Tap water at a temperature of 28 °C was used to remove the heat generated during the processes of condensing the ammonia vapor and absorbing the refrigerant again in the water. The COP calculated for the seven experimental runs was in the range 0.24–0.28 where typical values for an intermittent absorption refrigerator were in the range 0.28–0.36. The authors concluded that these results represent a clear possibility for using salinity gradient solar ponds for heating absorption refrigeration systems. Chinnappa et al. [131] reported constructional and operational features and some performance test results for a hybrid air-conditioning system consisting of a conventional R-22 vapor compression refrigeration machine cascaded with a solar driven ammonia–water single effect absorption system. The system is designed for air-conditioning applications in tropical areas. The evaporator of the ammonia system is utilized as a condenser for the R-22 compression system. This is found to yield considerable savings in electrical energy consumption by the compression system. They reported that for the test duration of 930–1500 h, the solar collection efficiency was in the range of 0.43–0.50, the absorption system coefficient of performance ranged from 0.59 to 0.72, the compressor alone system yielded a COP of 2.55, and the overall hybrid COP was about 5.

Khalid et al. [132] performed an exergy analysis on a liquid-desiccant-based, hybrid air-conditioning system that uses lithium bromide. The optimum desiccant mass-flow rate through the regenerator has been found to be about 30 kg/h m^2 for an ambient temperature of 40 °C. The maximum irreversibilities are generated at an ambient vapor pressure of 25 mmHg and a desiccant mass flow rate of 5 kg/h m^2. A liquid desiccant evaporative cooling system powered by solar energy with energy storage was proposed by Kessling et al. [129]. The dehumidified air was cooled by the evaporation of water in order to create a desired temperature. For a high energy storage capacity a high air to solution mass ratio is required to achieve great differences between salt inlet and outlet concentrations.

It is very difficult to keep the solar thermal system operating at a steady state throughout the day. Chen and Hihara [133] reported a type of absorption refrigeration cycle that is co-driven both by solar energy and electricity in order to improve the unsteady nature of the solar heat from the solar collector to the absorption system. They developed a thermodynamic model to describe and evaluate the performance of the cycle. Their numerical simulation model results showed the steady COP value of 0.8 for the new cycle, which was higher than the conventional cycle. They concluded that their cycle not only overcomes some shortcomings of the traditional absorption cycle with unsteady energy input from solar energy, but also increases the system's coefficient of performance.

11. Conclusion

A detailed literature survey of an absorption based refrigeration and air conditioning systems that are powered by solar energy is presented. Different system designs that are operating with different absorbate–absorbent working pairs along with the related theoretical and experimental work are discussed and demonstrated. These systems include both closed and open cycle types of machines. As a consequence, this present review is very helpful in terms of development and performance enhancement for each of these systems.

Acknowledgment

This work is supported and funded by the Egyptian Ministry of Research and Higher Education.

References

[1] Jaber JO, Badran OO, Abu-Shikhah N. Sustainable energy and environmental impact: role of renewables as clean and secure source of energy for the 21st century in Jordan. Clean Technologies and Environmental Policy 2004;6(3): 174–86.
[2] Lucas L. Iir news. International Journal of Refrigeration 1998;21(2):87–8.
[3] Choudhury B, Chatterjee PK, Sarkar JP. Review paper on solar-powered air-conditioning through adsorption route. Renewable and Sustainable Energy Reviews 2010;14(8):2189–95.
[4] Dunn GN, Bleil de Souza C, Marsh AJ, Knight IP. Measured building and air conditioning energy performance: an empirical evaluation of the energy performance of air conditioned office buildings in the UK. In: International conference on electricity efficiency in commercial buildings 2006. Frankfurt, Germany.
[5] Regulation (ec) no 2037/2000 of the European parliament and of the council of 29 June 2000 on substances that deplete the ozone layer, Official Journal of the European Communities 2000;244:1–24.
[6] Balaras CA, Grossman G, Henning H-M, Carlos A, Ferreira I, Podesser E, et al. Solar air conditioning in Europe—an overview. Renewable and Sustainable Energy Reviews 2007;11(2):299–314.
[7] Abu Hamdeh NH, Al-Muhtaseb MTA. Optimization of solar adsorption refrigeration system using experimental and statistical techniques. Energy Conversion and Management 2010;51(8):1610–5.
[8] Dueñas C, Pilatowsky I, Romero RJ, Oskam A, Finck AP. Dynamic study of the thermal behaviour of solar thermochemical refrigerator: barium chloride–ammonia for ice production. Solar Energy Materials and Solar Cells 2001;70(3): 401–13.
[9] Liu YL, Wang RZ. Performance prediction of a solar/gas driving double effect LiBr–H_2O absorption system. Renewable Energy 2004;29(10):1677–95.
[10] Sencan A, Yakut KA, Kalogirou SA. Exergy analysis of lithium bromide/water absorption systems. Renewable Energy 2005;30(5):645–57.
[11] Helm M, Keil C, Hiebler S, Mehling H, Schweigler C. Solar heating and cooling system with absorption chiller and low temperature latent heat storage: energetic performance and operational experience. International Journal of Refrigeration 2009;32(4):596–606.
[12] 2009 ASHRAE handbook—fundamentals (I-P edition). American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2009.
[13] Wang K, Abdelaziz O, Kisari P, Vineyard EA. State-of-the-art review on crystallization control technologies for water/LiBr absorption heat pumps. International Journal of Refrigeration 2011;34(6):1325–37.
[14] Jaruwongwittaya T, Chen G. A review: renewable energy with absorption chillers in Thailand. Renewable and Sustainable Energy Reviews 2010;14(5): 1437–44.
[15] Eicker U. Low energy cooling for sustainable buildings. United Kingdom: John Wiley & Sons; 2009.
[16] Nakahara N, Miyakawa Y, Yamamoto M. Experimental study on house cooling and heating with solar energy using flat plate collector. Solar Energy 1977;19(6):657–62.
[17] Yeung MR, Yuen PK, Dunn A, Cornish LS. Performance of a solar-powered air conditioning system in Hong Kong. Solar Energy 1992;48(5):309–19.

[18] Li ZF, Sumathy K. Experimental studies on a solar powered air conditioning system with partitioned hot water storage tank. Solar Energy 2001;71(5):285–97.

[19] Praene JP, Marc O, Lucas F, Miranville F. Simulation and experimental investigation of solar absorption cooling system in Reunion Island. Applied Energy 2011;88(3):831–9.

[20] Romero RJ, Rivera W, Pilatowsky I, Best R. Comparison of the modeling of a solar absorption system for simultaneous cooling and heating operating with an aqueous ternary hydroxide and with water/lithium bromide. Solar Energy Materials and Solar Cells 2001;70:301–8.

[21] Zhang X, Hu D. Performance simulation of the absorption chiller using water and ionic liquid 1-ethyl-3-methylimidazolium dimethylphosphate as the working pair. Applied Thermal Engineering 2011;31(16):3316–21.

[22] Ren J, Zhao Z, Zhang X. Vapor pressures, excess enthalpies, and specific heat capacities of the binary working pairs containing the ionic liquid 1-ethyl-3-methylimidazolium dimethylphosphate. Journal of Chemical Thermodynamics 2011;43(4):576–83.

[23] Zuo G, Zhao Z, Yan S, Zhang X. Thermodynamic properties of a new working pair: 1-ethyl-3-methylimidazolium ethylsulfate and water. Chemical Engineering Journal 2010;156(3):613–7.

[24] Abdelmessih AN, Abbas M, Al-Hashem A, Munson J. Ethylene glycol/water as working fluids for an experimental absorption cycle. Experimental Heat Transfer 2007;20(2):87–102.

[25] Romero RJ, Guillen L, Pilatowsky I. Monomethylamine–water vapour absorption refrigeration system. Applied Thermal Engineering 2005;25(5–6):867–76.

[26] Gutiérrez F. Behavior of a household absorption–diffusion refrigerator adapted to autonomous solar operation. Solar Energy 1988;40(1):17–23.

[27] Jakob U, Eicker U, Schneider D, Taki AH, Cook MJ. Simulation and experimental investigation into diffusion absorption cooling machines for air-conditioning applications. Applied Thermal Engineering 2008;28(10):1138–50.

[28] Sierra FZ, Best R, Holland FA. Experiments on an absorption refrigeration system powered by a solar pond. Heat Recovery Systems and CHP 1993;13(5):401–8.

[29] Worsøe-Schmidt P. A solar-powered solid-absorption refrigeration system. International Journal of Refrigeration 1979;2:75–82.

[30] Erhard A, Hahne E. Test and simulation of a solar-powered absorption cooling machine. Solar Energy 1997;59:155–62.

[31] Rivera CO, Rivera W. Modeling of an intermittent solar absorption refrigeration system operating with ammonia/lithium nitrate mixture. Solar Energy Materials and Solar Cells 2003;76:417–27.

[32] Steiu S, Salavera D, Bruno JC, Coronas A. A basis for the development of new ammonia–water–sodium hydroxide absorption chillers. International Journal of Refrigeration 2009;32(4):577–87.

[33] Bansal NK, Blumenberg J, Kavasch HJ, Roettinger T. Performance testing and evaluation of solid absorption solar cooling unit. Solar Energy 1997;61:127–40.

[34] Medrano M, Bourouis M, Coronas A. Double-lift absorption refrigeration cycles driven by low-temperature heat sources using organic fluid mixtures as working pairs. Applied Energy 2001;68:173–85.

[35] Boer D, Valles M, Coronas A. Performance of double effect absorption compression cycles for air-conditioning using methanol–TEGDME and TFE–TEGDME systems as working pairs. International Journal of Refrigeration 1998;21(7):542–55.

[36] Zhai XQ, Qu M, Li Y, Wang RZ. A review for research and new design options of solar absorption cooling systems. Renewable and Sustainable Energy Reviews 2011;15(9):4416–23.

[37] Lazzarin RM, Romagnoni P, Casasola L. Two years of operation of a large solar cooling plant. International Journal of Refrigeration 1993;16(3):185–90.

[38] Asdrubali F, Grignaffini S. Experimental evaluation of the performances of a H_2O–LiBr absorption refrigerator under different service conditions. International journal of refrigeration 2005;28(4):489–97.

[39] Syed A, Izquierdo M, Rodríguez P, Maidment G, Missenden J, Lecuona A, et al. A novel experimental investigation of a solar cooling system in Madrid. International Journal of Refrigeration 2005;28(6):859–71.

[40] Pongtornkulpanich A, Thepa S, Amornkitbamrung M, Butcher C. Experience with fully operational solar-driven 10-ton LiBr/H_2O single-effect absorption cooling system in Thailand. Renewable Energy 2008;33(5):943–9.

[41] Rosiek S, Batlles FJ. Integration of the solar thermal energy in the construction: analysis of the solar-assisted air-conditioning system installed in CIESOL building. Renewable Energy 2009;34(6):1423–31.

[42] Ortiz M, Barsun H, He H, Vorobieff P, Mammoli A. Modeling of a solar-assisted HVAC system with thermal storage. Energy and Buildings 2010;42(4):500–9.

[43] Mammoli A, Vorobieff P, Barsun H, Burnett R, Fisher D. Energetic economic and environmental performance of a solar-thermal-assisted HVAC system. Energy and Buildings 2010;42(9):1524–35.

[44] Agyenim F, Knight I, Rhodes M. Design and experimental testing of the performance of an outdoor LiBr/H_2O solar thermal absorption cooling system with a cold store. Solar Energy 2010;84(5):735–44.

[45] Bakhtiari B, Fradette L, Legros R, Paris J. A model for analysis and design of H_2O–LiBr absorption heat pumps. Energy Conversion and Management 2011;52(2):1439–48.

[46] Ng KC, Bong TY, Chua HT, Bao HL. Theoretical and experimental analysis of an absorption chiller. International Journal of Refrigeration 1994;17(5):351–8.

[47] Ng KC, Chua HT, Han Q, Kashiwagi T, Akisawa A, Tsurusawa T, et al. Thermodynamic modeling of absorption chiller and comparison with experiments. Heat Transfer Engineering 1999;20(2):42–51.

[48] Joudi KA, Lafta AH. Simulation of a simple absorption refrigeration system. Energy Conversion and Management 2001;42(13):1575–605.

[49] Florides GA, Kalogirou SA, Tassou SA, Wrobel LC. Design and construction of a LiBr–water absorption machine. Energy Conversion and Management 2003;44(15):2483–508.

[50] Kilic M, Kaynakli O. Theoretical study on the effect of operating conditions on performance of absorption refrigeration system. Energy Conversion and Management 2007;48(2):599–607.

[51] Aphornratana S, Eames IW. Thermodynamic analysis of absorption refrigeration cycles using the second law of thermodynamics method. International Journal of Refrigeration 1995;18(4):244–52.

[52] Talbi MM, Agnew B. Exergy analysis: an absorption refrigerator using lithium bromide and water as the working fluids. Applied Thermal Engineering 2000;20(7):619–30.

[53] Lee SF, Sherif SA. Thermodynamic analysis of a lithium bromide/water absorption system for cooling and heating applications. International Journal of Energy Research 2001;25(11):1019–31.

[54] Kilic M, Kaynakli O. Second law-based thermodynamic analysis of water lithium bromide absorption refrigeration system. Energy 2007;32(8):1505–12.

[55] Kaynakli O, Yamankaradeniz R. Thermodynamic analysis of absorption refrigeration system based on entropy generation. Current Science 2007;92(4):472–9.

[56] Aphornratana S, Sriveerakul T. Experimental studies of a single-effect absorption refrigerator using aqueous lithium-bromide: effect of operating condition to system performance. Experimental Thermal and Fluid Science 2007;32(2):658–69.

[57] Engler M, Grossman G, Hellmann MH. Comparative simulation and investigation of ammonia-water: absorption cycles for heat pump applications. International Journal of Refrigeration 1997;20(7):504–16.

[58] Grossman G, Zaltash A. ABSIM—modular simulation of advanced absorption systems. International Journal of Refrigeration 2001;24(6):531–43.

[59] Florides GA, Kalogirou SA, Tassou SA, Wrobel LC. Modelling, simulation and warming impact assessment of a domestic-size absorption solar cooling system. Applied Thermal Engineering 2002;22(12):1313–25.

[60] Joudi KA, Abdul-Ghafour QJ. Development of design charts for solar cooling systems. Part I: computer simulation for a solar cooling system and development of solar cooling design charts. Energy Conversion and Management 2003;44(2):313–39.

[61] Atmaca I, Yigit A. Simulation of solar-powered absorption cooling system. Renewable Energy 2003;28(8):1277–93.

[62] Assilzadeh F, Kalogirou SA, Ali Y, Sopian K. Simulation and optimization of a LiBr solar absorption cooling system with evacuated tube collectors. Renewable Energy 2005;30(8):1143–59.

[63] Mittelman G, Kribus A, Dayan A. Solar cooling with concentrating photovoltaic/thermal (CPVT) systems. Energy Conversion and Management 2007;48(9):2481–90.

[64] Mazloumi M, Naghashzadegan M, Javaherdeh K. Simulation of solar lithium bromide-water absorption cooling system with parabolic trough collector. Energy Conversion and Management 2008;49(10):2820–32.

[65] Balghouthi M, Chahbani MH, Guizani A. Feasibility of solar absorption air conditioning in Tunisia. Building and Environment 2008;43(9):1459–70.

[66] Calise F. Thermoeconomic analysis and optimization of high efficiency solar heating and cooling systems for different Italian school buildings and climates. Energy and Buildings 2010;42(7):992–1003.

[67] Prasartkaew B, Kumar S. A low carbon cooling system using renewable energy resources and technologies. Energy and Buildings 2010;42(9):1453–62.

[68] Monné C, Alonso S, Palacín F, Serra L. Monitoring and simulation of an existing solar powered absorption cooling system in Zaragoza (Spain). Applied Thermal Engineering 2011;31(1):28–35.

[69] Al-Alili A, Hwang Y, Radermacher R, Kubo I. A high efficiency solar air conditioner using concentrating photovoltaic/thermal collectors. Applied Energy 2012;93:138–47.

[70] Ziegler F. Recent developments and future prospects of sorption heat pump systems. International Journal of Thermal Sciences 1999;38:191–208.

[71] Herold KE, Radermacher R, Klein SA. Absorption chillers and heat pumps. Boca Raton, Florida: CRC Press; 1996.

[72] Ziegler F, Alefeld G. Coefficient of performance of multistage absorption cycles. International Journal of Refrigeration 1987;10(5):285–95.

[73] Alizadeh S. Multi-pressure absorption cycles in solar refrigeration: a technical and economical study. Solar Energy 2000;69(1):37–44.

[74] Arivazhagan S, Saravanan R, Renganarayanan S. Experimental studies on HFC based two-stage half effect vapour absorption cooling system. Applied Thermal Engineering 2006;26(14–15):1455–62.

[75] Gebreslassie BH, Medrano M, Boer D. Exergy analysis of multi-effect water–LiBr absorption systems: from half to triple effect. Renewable Energy 2010;35(8):1773–82.

[76] Kim DS, Machielsen CHM. Evaluation of air-cooled solar absorption cooling systems. In: Proceedings of ISHPC, Shanghai, China; 2002.

[77] Kim DS, Infante Ferreira CA. Air cooled LiBr–water absorption chillers for solar air conditioning in extremely hot weathers. Energy Conversion and Management 2009;50(4):1018–25.
[78] Sumathy K, Huang Z, Li ZF. Solar absorption cooling with low grade heat source—a strategy of development in South China. Solar Energy 2002; 72(2):155–65.
[79] Izquierdo M, Venegas M, Rodríguez P, Lecuona A. Crystallization as a limit to develop solar air-cooled LiBr–H_2O absorption systems using low-grade heat. Solar Energy Materials and Solar Cells 2004;81(2):205–16.
[80] Izquierdo M, Venegas M, García N, Palacios E. Exergetic analysis of a double stage LiBr–H_2O thermal compressor cooled by air/water and driven by low grade heat. Energy Conversion and Management 2005;46(7–8):1029–42.
[81] Figueredo GR, Bourouis M, Coronas A. Thermodynamic modelling of a two-stage absorption chiller driven at two-temperature levels. Applied Thermal Engineering 2008;28(2-3):211–7.
[82] Xu GP, Dai YQ, Tou KW, Tso CP. Theoretical analysis and optimization of a double-effect series-flow-type absorption chiller. Applied Thermal Engineering 1996;16(12):975–87.
[83] Arun MB, Maiya MP, Murthy SS. Performance comparison of double effect parallel flow and series flow water lithium bromide absorption systems. Applied Thermal Engineering 2001;21:1273–9.
[84] Kaushik SC, Arora A. Theoretical analysis of LiBr/H_2O absorption refrigeration systems. International Journal of Energy Research 2009;33(15): 1321–40.
[85] Gomri R. Investigation of the potential of application of single effect and multiple effect absorption cooling systems. Energy Conversion and Management 2010;51(8):1629–36.
[86] Farshi LG, Mahmoudi SMS, Rosen MA. Analysis of crystallization risk in double effect absorption refrigeration systems. Applied Thermal Engineering 2011;31(10):1712–7.
[87] Tierney MJ. Options for solar-assisted refrigeration—trough collectors and double-effect chillers. Renewable Energy 2007;32(2):183–99.
[88] Qu M, Yin H, Archer HD. A solar thermal cooling and heating system for a building: experimental and model based performance analysis and design. Solar Energy 2010;84(2):166–82.
[89] Venkatesh A, Mani A. Comparison of performances of single stage and two stage intermittent ammonia–water solar refrigeration systems. Solar & Wind Technology 1989;6(1):75–8.
[90] Staicovici MD. An autonomous solar ammonia–water refrigeration system. Solar Energy 1986;36(2):115–24.
[91] Erhard A, Spindler K, Hahne E. Test and simulation of a solar powered solid sorption cooling machine. International Journal of Refrigeration 1998;21(2): 133–41.
[92] Rivera W, Moreno-Quintanar G, Rivera CO, Best R, Martínez F. Evaluation of a solar intermittent refrigeration system for ice production operating with ammonia/lithium nitrate. Solar Energy 2011;85(1):38–45.
[93] Moreno-Quintanar G, Rivera W, Best R. Comparison of the experimental evaluation of a solar intermittent refrigeration system for ice production operating with the mixtures $NH_3/LiNO_3$ and $NH_3/LiNO_3/H_2O$. Renewable Energy 2012;38(1):62–8.
[94] Mani A, Venkatesh A. A two stage intermittent solar refrigeration system—evaluation of salient parameters. Energy Conversion and Management 1986;26(3–4):271–6.
[95] Pridasawas W. Solar driven refrigeration systems with focus on the ejector cycle. PhD thesis, Royal Institute of Technology Stockholm, Sweden; 2006.
[96] Das K, Mani A. Comparative study of cycle performance for a two stage intermittent solar refrigerator working with R22-absorbent combinations. Energy Conversion and Management 1996;37(1):87–93.
[97] Chen J, Kim KJ, Herold KE. Performance enhancement of a diffusion–absorption refrigerator. International Journal of Refrigeration 1996;19(3): 208–18.
[98] Ziapour BM, Tavakoli M. Performance study on a diffusion absorption refrigeration heat pipe cycle. International Journal of Thermal Sciences 2011;50(4):592–8.
[99] Wang Q, Gong L, Wang JP, Sun TF, Cui K, Chen GM. A numerical investigation of a diffusion absorption refrigerator operating with the binary refrigerant for low temperature applications. Applied Thermal Engineering 2011;31(10):1763–9.
[100] Zohar A, Jelinek M, Levy A, Borde I. Performance of diffusion absorption refrigeration cycle with organic working fluids. International Journal of Refrigeration 2009;32(6):1241–6.
[101] Zohar A, Jelinek M, Levy A, Borde I. The influence of diffusion absorption refrigeration cycle configuration on the performance. Applied Thermal Engineering 2007;27(13):2213–9.
[102] Zohar A, Jelinek M, Levy A, Borde I. Numerical investigation of a diffusion absorption refrigeration cycle. International Journal of Refrigeration 2005;28(4):515–25.
[103] Sozen A, Menlik T, Ozbas E. The effect of ejector on the performance of diffusion absorption refrigeration systems: an experimental study. Applied Thermal Engineering 2012;33–44:44–53.
[104] Koyfman A, Jelinek M, Levy A, Borde I. An experimental investigation of bubble pump performance for diffusion absorption refrigeration system with organic working fluids. Applied Thermal Engineering 2003;23(15): 1881–94.
[105] Saravanan R, Maiya MP. Experimental analysis of a bubble pump operated H_2O–LiBr vapour absorption cooler. Applied Thermal Engineering 2003; 23(18):2383–97.
[106] Valizadeh H, Ashrafi N. A continuous cycle solar thermal refrigeration system. Renewable Energy 1996;9(1–4):632–40.
[107] Ben Ezzine N, Garma R, Bourouis M, Bellagi A. Experimental studies on bubble pump operated diffusion absorption machine based on light hydrocarbons for solar cooling. Renewable Energy 2010;35(2):464–70.
[108] Ben Ezzine N, Garma R, Bellagi A. A numerical investigation of a diffusion–absorption refrigeration cycle based on R124-DMAC mixture for solar cooling. Energy 2010;35(5):1874–83.
[109] Kaushik SC, Kaudinya JV. Open cycle absorption cooling—a review. Energy Conversion and Management 1989;29(2):89–109.
[110] Kaushik SC, Kaudinya JV, Yadav YK. Studies on some solar collector/regenerator systems for open cycle absorption air conditioning/liquid desiccant cooling systems. Heat Recovery Systems and CHP 1992;12(4): 357–63.
[111] Collier RK. The analysis and simulation of an open cycle absorption refrigeration system. Solar Energy 1979;23(4):357–66.
[112] Kumar P, Devotta S. Modelling of the thermal behaviour of a solar regenerator for open-cycle cooling systems. Applied Energy 1989;33(4): 287–95.
[113] Hawlader MA, Stact AP, Wood B. Performance evaluation of glazed and unglazed collector/regenerators in a liquid absorbent open-cycle absorption cooling system. International Journal of Solar Energy 1992;11(3–4):135–64.
[114] Haim I, Grossman G, Shavit A. Simulation and analysis of open cycle absorption systems for solar cooling. Solar Energy 1992;49(6):515–34.
[115] Yang R, Yan WJ. Simulation study for an open-cycle absorption solar-cooling system operated in a humid area. Energy 1992;17(7):649–55.
[116] Yang R, Wang P. The optimum glazing height of a glazed solar collector/regenerator for open-cycle absorption cooling. Energy 1994;19(9):925–31.
[117] Yang R, Wang P. A simulation study of performance evaluation of single-glazed and double-glazed collectors/regenerators for an open-cycle absorption solar cooling system. Solar Energy 2001;71(4):263–8.
[118] Sultan GI, Hamed AM, Sultan AA. The effect of inlet parameters on the performance of packed tower-regenerator. Renewable Energy 2002;26(2): 228–71.
[119] Hamed AM. Desorption characteristics of desiccant bed for solar dehumidification/humidification air conditioning systems. Renewable Energy 2003;28(13):2099–111.
[120] Alizadeh S, Saman WY. Modeling and performance of a forced flow solar collector/regenerator using liquid desiccant. Solar Energy 2002;72(2): 143–54.
[121] Kabeel AE. Augmentation of the performance of solar regenerator of open absorption cooling system. Renewable Energy 2005;30(3):327–38.
[122] Zeidan EB, Aly AA, Hamed AM. Modeling and simulation of solar-powered liquid desiccant regenerator for open absorption cooling cycle. Solar Energy 2011;85(11):2977–86.
[123] Aly AA, Zeidan EB, Hamed AM. Performance evaluation of open-cycle solar regenerator using artificial neural network technique. Energy and Buildings 2011;43(2–3):454–7.
[124] Aly AA, Zeidan EB, Hamed AM. Solar-powered open absorption cycle modeling with two desiccant solutions. Energy Conversion and Management 2011;52(7):2768–76.
[125] Hellmann HM, Grossman G. Simulation and analysis of an open-cycle dehumidifier–evaporator–regenerator (DER) absorption chiller for low-grade heat utilization. International Journal of Refrigeration 1995;18(3): 177–89.
[126] Pohl JP, Hellmann HM, Grossman G. Investigation and comparison of two configurations of a novel open-cycle absorption chiller. International Journal of Refrigeration 1998;21(2):142–9.
[127] Gommed K, Grossman G, Ziegler F. Experimental investigation of a LiCl–water open absorption system for cooling and dehumidification ASME. Transactions Journal of Solar Energy Engineering 2004;126(2):710–5.
[128] Gommed K, Grossman G. Experimental investigation of a liquid desiccant system for solar cooling and dehumidification. Solar Energy 2007;81(1): 131–8.
[129] Kessling W, Laevemann E, Kapfhammer C. Energy storage for desiccant cooling systems component development. Solar Energy 1998;64(4–6): 209–21.
[130] Kaushik SC, Yadav YK. Thermodynamic design and assessment of hybrid double absorption solar cooling systems. Heat Recovery Systems and CHP 1991;11(4):255–62.
[131] Chinnappa JCV, Crees MR, Murthy SS, Srinivasan K. Solar-assisted vapor compression/absorption cascaded air-conditioning systems. Solar Energy 1993;50(5):453–8.
[132] Khalid ACS, Gandhidasan P, Zubair SM, Al-Farayedhi AA. Exergy analysis of a liquid-desiccant-based, hybrid air-conditioning system. Energy 1998;23(1): 51–9.
[133] Chen G, Hihara E. A new absorption refrigeration cycle using solar energy. Solar Energy 1999;66(6):479–82.